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Suppression of High Speed Turbulent Flames in a Detonation/Deflagration Tube

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ABSTRACT

Live-fire, full-scale testing has been conducted at Wright-Patterson Air Force Base to identify an agent to replace CF_3Br (halon 1301) for suppressing fires in military aircraft dry bays. The three chemicals being considered (C_2HF_5, HFC-125; C_3F_8, FC-218; and CF_3I, halon 13001) had been evaluated in a previous laboratory study, in which unique properties of each chemical were identified in small-scale experiments. The CF_3I required the least mass to suppress a turbulent spray flame but performed less-well in suppressing a quasi-detonation. FC-218 performed the best in the presence of a quasi-detonation. HFC-125 was recommended previously as a candidate because of its superior dispersion characteristics; however, this chemical produced large over-pressures in the detonation/deflagration tube. The high pressures motivated the current study to determine the initial conditions which would lead to dangerous conditions, and to explore less extreme situations more representative of a realistic threat. The detonation/deflagration tube was lengthened from 7.5 to 10 m, the spiral insert in the test section was removed, and the fuel was switched from ethene to propane to produce uninhibited pressure ratios below 9:1 and turbulent flame speeds between 300 and 600 m/s. The FC-218 provided the most consistent performance in this new series of experiments which examined lean, stoichiometric and rich initial conditions. The CF_3I had the greatest positive impact at low concentrations, but exhibited non-monotonic behavior of flame speed and shock pressure ratio at increasing concentrations. Large pressure build ups were not observed during suppression of the propane/air mixtures under the current set of conditions. None of the agents could be ruled out for dry bay applications based upon the results of this study.

ACKNOWLEDGEMENT

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1. Background

The elimination of new production of CF_3Br (halon 1301) has forced the manufacturers, owners, and users of aircraft to search for alternatives. In an earlier study (Grosshandler et al., 1994), candidate replacements for halon 1301 for protection of aircraft dry bays were ranked according to how well each could suppress a turbulent spray flame and a quasi-detonation. A dry bay is a normally confined space adjacent to a fuel tank in which a combustible mixture and an ignition source could co-exist following penetration by an anti-aircraft projectile. They vary considerably in volume, typically being in the range of 0.2 to 3.0 m^3. They are located in the wings and fuselage, and their shape is most often irregular, as can be seen in Figure 1. Aspect ratios up to 10:1 are not uncommon. The bays may or may not be ventilated, and are usually cluttered with electronic, hydraulic and mechanical components. Compared to the events leading to engine nacelle fire suppression, the required timing is two orders-of-magnitude faster for dry bay protection. High speed infrared detectors sense the initial penetration of the projectile and automatically arm and fire the halon bottle. The storage bottles are located directly in or adjacent to the protected space to minimize the time needed to flood the volume totally. The entire suppression sequence occurs in less than 100 ms and requires no crew intervention.

The previous study (Grosshandler et al., 1994) was concerned with establishing a comprehensive experimental program to screen the performance of over a dozen agents. The experiments were designed to cover the range of conditions that might occur in a dry bay. Based on data taken during the research, two agents, C_3F_8 (FC-218) and C_2HF_5 (HFC-125), were recommended by NIST for full-scale evaluation in the dry bay facility at Wright-Patterson AFB. Heptafluoropropane (C_3HF_7, or HFC-227ea) was recommended as a back-up to HFC-125, because the former did not exhibit the dangerously high over-pressures observed when the latter was tested in the detonation/deflagration tube. There was considerable concern expressed by NIST with HFC-227ea, however, about its ability to disperse quickly and uniformly in a dry bay because it has a relatively high boiling point and Jakob number. Iodotrifluoromethane (CF_3I) was also recommended by NIST for limited full-scale testing, with the proviso that a sufficient supply of pure agent be obtained.

Three chemicals were selected by the Technology Transition Team to be included in the complete full-scale experimental matrix (Carbaugh, 1993): HFC-125, FC-218 and CF_3I. In the laboratory-scale NIST turbulent spray burner, HFC-125 and FC-218 required nearly identical amounts of material (on a storage volume basis) to suppress the spray flame. Iodotrifluoromethane required less than half the storage volume. Using the detonation/ deflagration tube apparatus, the volume factor (VF) measured for FC-218 is lower than that of HFC-125. The most significant observed difference between HFC-125 and FC-218 was the high over-pressure experienced for HFC-125 concentrations below 25% (mass). With the deflagration/detonation tube operating with a lean ethene/air mixture, 21% HFC-125 in the test section produced a quasi-detonation with a pressure ratio of 36:1, double the pressure build-up when no agent was present. The FC-218 behaved quite differently, and effectively reduced the pressure ratio at concentrations near 21%.

Few flame suppression experiments had been conducted with CF_3I that were applicable to dry bays. The previous detonation/deflagration tube results indicated an unusual behavior that could also be observed with CF_3Br, but to a lesser extent. Both chemicals were equally effective in low concentrations at reducing the pressure build-up. At mass fractions greater than about 10% the chemistry is altered and the pressures began to rise. Increasing the CF_3Br concentration benefitted suppression at mass fractions greater than 20%, and total suppression of the flame occurred above 30%. Pressure ratios in the CF_3I tests continued to rise with concentration up to a mass fraction of 30%, reaching a pressure ratio greater than the uninhibited mixture. That is, adding 30% CF_3I to a lean ethene/air flame exacerbated the situation. It took a mass fraction of almost 45% to completely suppress the pressure build-up.

The maximum pressure ratios observed in full-scale live-fire testing of uninhibited propane air mixtures are less than 7:1, and photographic evidence from full-scale dry bay testing suggests that turbulent flame speeds are below 300 m/s (Bennett, 1994). The previous experiments created uninhibited pressure ratios up to 25:1 and quasi-detonation velocities over 1100 m/s. The main problem addressed in the current research project is whether or not a dangerous over-pressure can arise during suppression with HFC-125 under different sets of achievable conditions in the detonation/deflagration tube that represent a more realistic threat scenario. A related, but less severe, problem existed with CF_3I, in which small amounts of the chemical effectively inhibited the quasi-detonation; but as the concentration was increased, pressures increased to a point exceeding the uninhibited situation. It is unknown why this occurred, making it impossible to predict the behavior of CF_3I under substantially different conditions. The performance of CF_3I in less severe operating conditions was the second major issue investigated in this study.

The specific objectives of the current research project are the following:

a. To determine the effectiveness of HFC-125, relative to FC-218, in suppressing high speed turbulent propane/air flames using the detonation/deflagration tube apparatus.

b. To determine the conditions in the detonation/deflagration tube (equivalence ratio, tube geometry) which lead to excessive pressure build-up during suppression by HFC-125 of propane/air mixtures initially at room temperature and pressure.

c. To determine the effectiveness of CF_3I, relative to FC-218, in suppressing high speed turbulent propane/air flames using the detonation/deflagration tube apparatus.

d. To recommend a ranking of the three agents for full-scale dry bay applications based upon the current and previous suppression experiments.

2. Technical Approach and Task Summary

The detonation/deflagration tube is a unique apparatus for evaluating a fire suppressant in a highly dynamic situation. A shock wave precedes the flame, with obstructions in the flow, if any, promoting intense mixing of the fresh reactants with the combustion products and causing the pressure waves to interact with the mixing region. Given enough distance, the initially subsonic flame (deflagration) can accelerate dramatically, reaching the supersonic regime (detonation), and increasing the temperature of the reaction zone behind the shock as well as further adding to the heat release rate. Depending upon the geometric details, the wave can approach its theoretical Chapman-Jouguet velocity and accompanying high pressure ratio. Even a slight variation in composition of the reactants near the limit of detonation can cause a dramatic change in the wave velocity and cause destructive pressures to be attained.

Extensive literature exists describing the kinetics and dynamics of flame/shock wave systems formed within classical detonation tubes (*e.g.*, Lefebvre *et al.*, 1992; Nettleton, 1987; Lee, 1984; Baker *et al.*, 1983; Westbrook, 1982). Chapman and Wheeler (1926) were the first to note that a methane/air flame could be accelerated to a terminal velocity in a shorter distance within a circular tube by placing obstacles into the flow. Lee, *et al.* (1984) built on this observation to study quasi-detonations in hydrogen/air and hydrocarbon/air mixtures.

A quasi-detonation propagates more slowly than a true detonation due to pressure losses in the flow, but its structure is more complex than a true detonation, and the mechanism of its propagation is not fully understood. Although obstructed flow is more difficult to analyze than the flow in a smooth-walled tube, the complex arrangement has been chosen for the current study because it more closely simulates a potentially damaging condition in the dry bay. The present construction of the detonation/deflagration tube facility is designed to produce both obstructed and unobstructed flow conditions.

Because the fire extinguishant is unlikely to be released prior to the establishment of a turbulent flame, the traditional experiment in which the flame inhibitor is premixed with the fuel and air prior to ignition does not replicate the chemistry critical to the actual situation. Each dry bay on an aircraft has a different geometry, and the release of the agent once a fire is detected is highly variable.

Shock/flame wave velocity and pressure ratio were the two dependent parameters which were measured as a means to characterize the extent of flame suppression. The velocity was determined by the time it takes for the pressure wave to travel the distance between two pressure transducers. The pressure ratio was evaluated from the average amplitude of the first pressure pulse recorded by each transducer, normalized by the initial pressure. The desire to rapidly suppress a flame and the associated pressure build up in such a situation was the primary objective behind this study.

A number of specific tasks were performed using the detonation/deflagration tube apparatus. First, experiments were performed to determine the range of Mach numbers and pressure ratios obtainable in the tube using propane, rather than ethene, in the apparatus. The objective of this task was to produce in a predictable manner high speed turbulent flames (with Mach numbers between 1 and 2 and pressure ratios between 3 and 10) by manipulating the initial conditions in the tube. The variables at our disposal were the propane/air ratio, the fuel partial pressure, and the length of the tube and internal spiral. The conditions which led to repeatable subsonic flames were noted. Next, the pressure ratios and Mach numbers were measured in lean, stoichiometric and rich propane/air mixtures over a range of HFC-125, FC-218 and CF_3I mass fractions in the test section of the detonation/ deflagration tube. The initial conditions were chosen to produce uninhibited Mach numbers below 2.0 and pressure ratios smaller than 10.

3. Experimental Set-up

3.1 Design. The two-sectional detonation/deflagration tube was designed (Gmurczyk, *et al.*, 1993, 1994) to examine the performance of the alternative agents in a highly dynamic situation, in which the pressure effects on the chemistry are thought to be important. Using the detonation/deflagration tube, the effectiveness of a fire fighting agent in suppressing a high speed, premixed flame or quasi-detonation can be rated by the extent to which it decelerates the propagating flame and simultaneously attenuates the hazardous shock which is always ahead of the flame.

A primary feature of the set-up is that the conditions of the ignition event do not affect the suppression process itself. Also, because an agent of interest is premixed with the fuel and air in a section of the tube separated from the ignition event, the influence of entrainment of the agent into the flame is minimized. The tube is closed to allow the increase in pressure to interact with the combustion chemistry.

The facility is shown schematically in Figure 1. The left hand side of the picture shows a fragment of the driver (flame/shock generation) section of the tube separated by a partition from the test (flame/shock suppression/attenuation) section of the tube on the right hand side of the picture. The flame/shock system propagating within a combustible mixture is fully established before entering the region occupied by a suppressant premixed with the same combustible mixture.

The driver section is 5 m long (see Figure 2) and is equipped at the closed end with a spark plug. This section is filled with the combustible mixture of ethene or propane and air of various compositions. The gas handling system (see Figure 3) consists of a vacuum pumping network; pressurized gas cylinders for the fuel, oxidizer and agent; and a dual circulating pump. The ignition energy is delivered in a microexplosion of a tin droplet short-circuiting the tips of nichrome electrodes connected to an 80 V power supply. Spiral-shaped obstructions made of 6.4 mm stainless steel rods with a pitch equal to the inner diameter of the tube are inserted into the tube, to produce an area blockage ratio of 44%, close to the value which is known to promote a high-speed or quasi-detonation regime of combustion.

The second section of the detonation/deflagration tube contains the gaseous agent along with the same fuel/air mixture used in the driver section. The diameter is the same and its length is either 2.5 m (ethene/air/suppressant mixtures in the presence of the spiral insert) or 5 m (propane/air/suppressant mixtures without the spiral insert). The longer tube is used when no spiral is applied, so as to avoid unwanted interferences from shock reflections from the end of the tube.

The two sections are separated from each other by a 50 mm inner diameter, stainless steel, high vacuum gate valve (partition), which remains closed until just before ignition. Pressure transducers (see Figure 4) and photodiodes (see Figures 5 and 6) are located along the test section to monitor the strength and speed of the combustion wave. Their output is recorded either with a computer or with a fast, multi-channel, digital storage oscilloscope. In the latter case the data are also stored in the computer, since full communication is possible between the scope and computer.

3.2 Operation. The whole system is evacuated to 10^{-1} Pa before filling the two sections separately with the desired mixtures, which are attained through the method of static partial pressures. The fuel/air ratio and total pressures are held constant across the gate valve. After filling, the gases are homogenized independently using a double, spark-free circulating pump, recirculating the entire tube volume a total of 20 times. The mixtures are then left for five minutes to become quiescent. About ten seconds prior to ignition, the gate valve is opened manually. After ignition, the flame propagates into the driver section and accelerates quickly due to the intense turbulence created by the interactions of the flow with the obstacles. This generates a shock wave ahead of the flame. After passing through the open gate valve the flame/shock system encounters the same combustible mixture and a certain amount of agent in the test section. Depending on the concentration of the agent, the flame may be extinguished (or enhanced) and the pressure wave may be attenuated (or amplified).

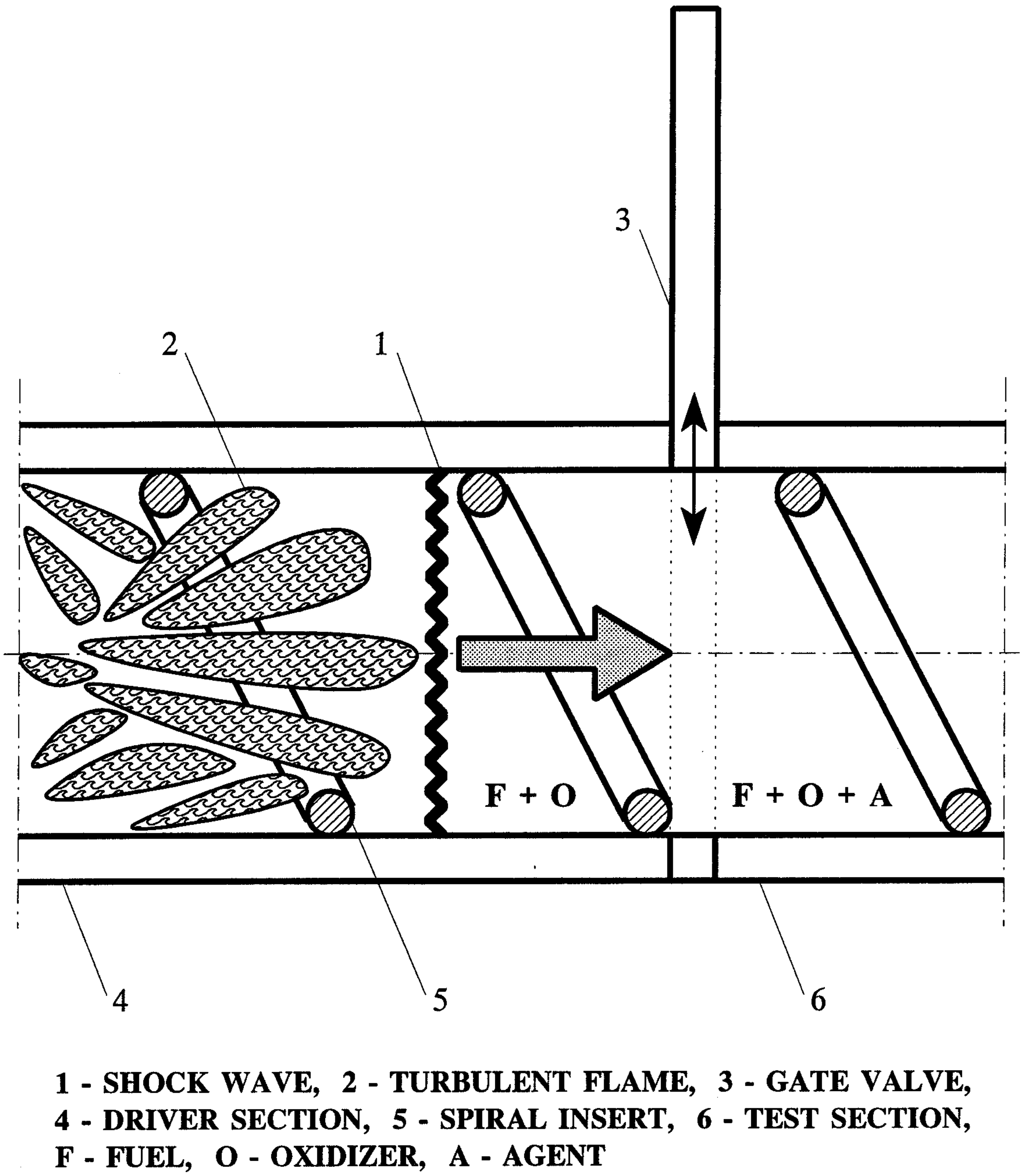
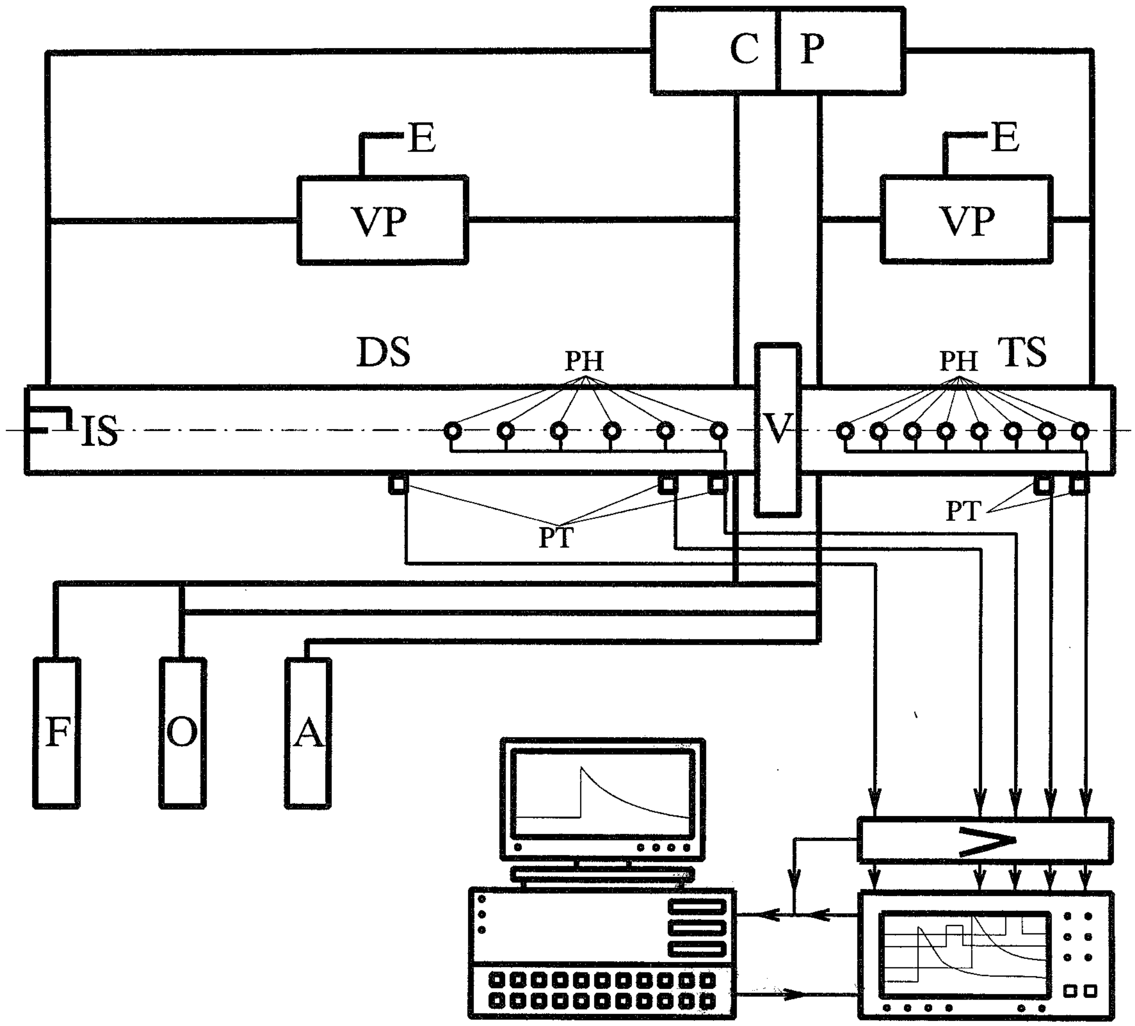
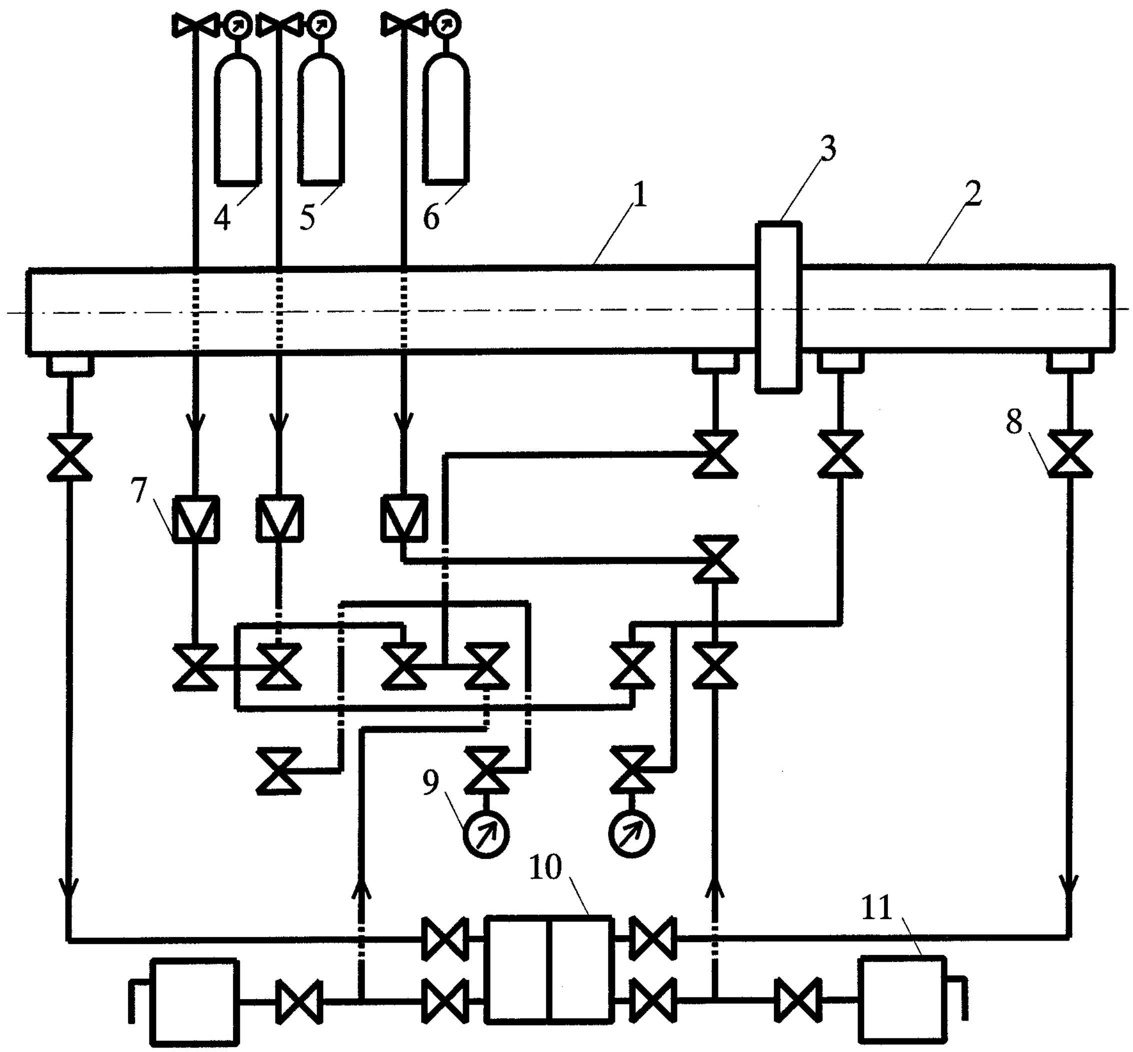


Figure 1 Schematic of the combustion/suppression process in the detonation/deflagration tube



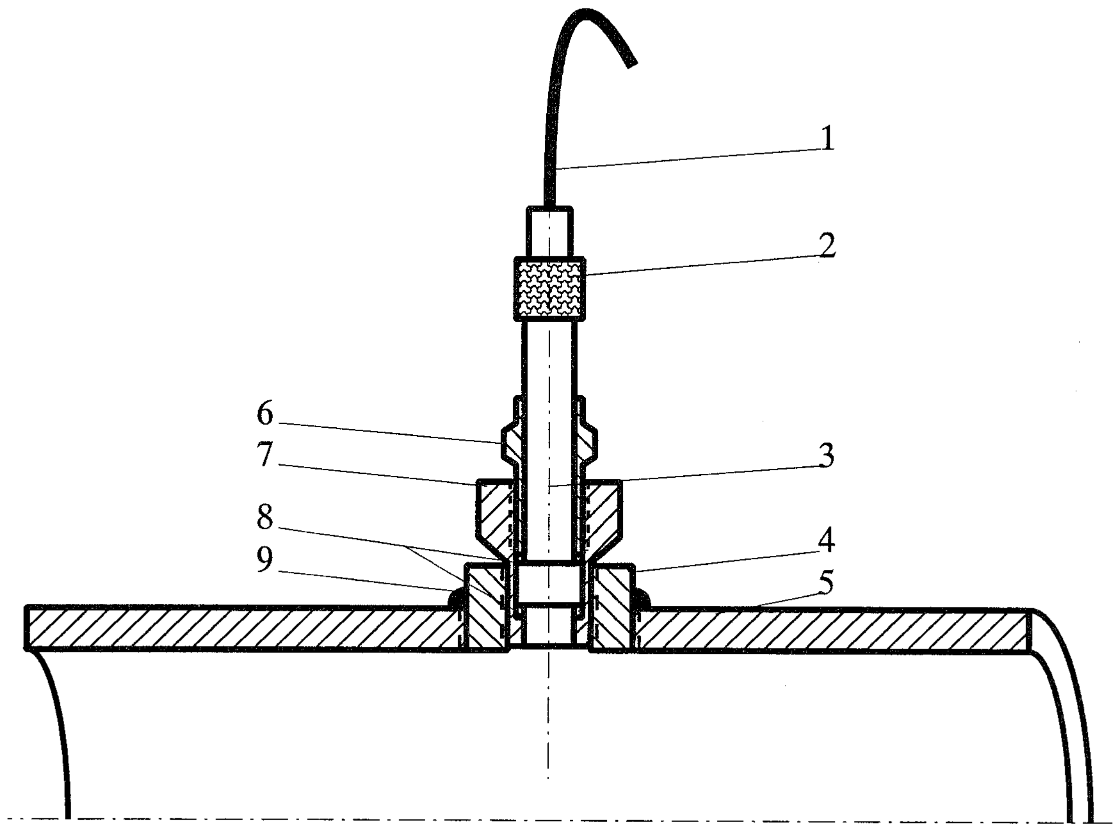
DS - DRIVER SECTION, TS - TEST SECTION, V - GATE VALVE,
IS - IGNITION SYSTEM, CP - CIRCULATION PUMP,
VP - VACUUM PUMP, E - EXHAUST, F - FUEL, O - OXIDIZER,
A - AGENT, PH - FAST PHOTODIODE, PT - PIEZOELECTRIC
PRESSURE TRANSDUCER, > - BLOCK OF AMPLIFIERS

Figure 2 Schematic of the detonation/deflagration tube facility designed and installed at NIST



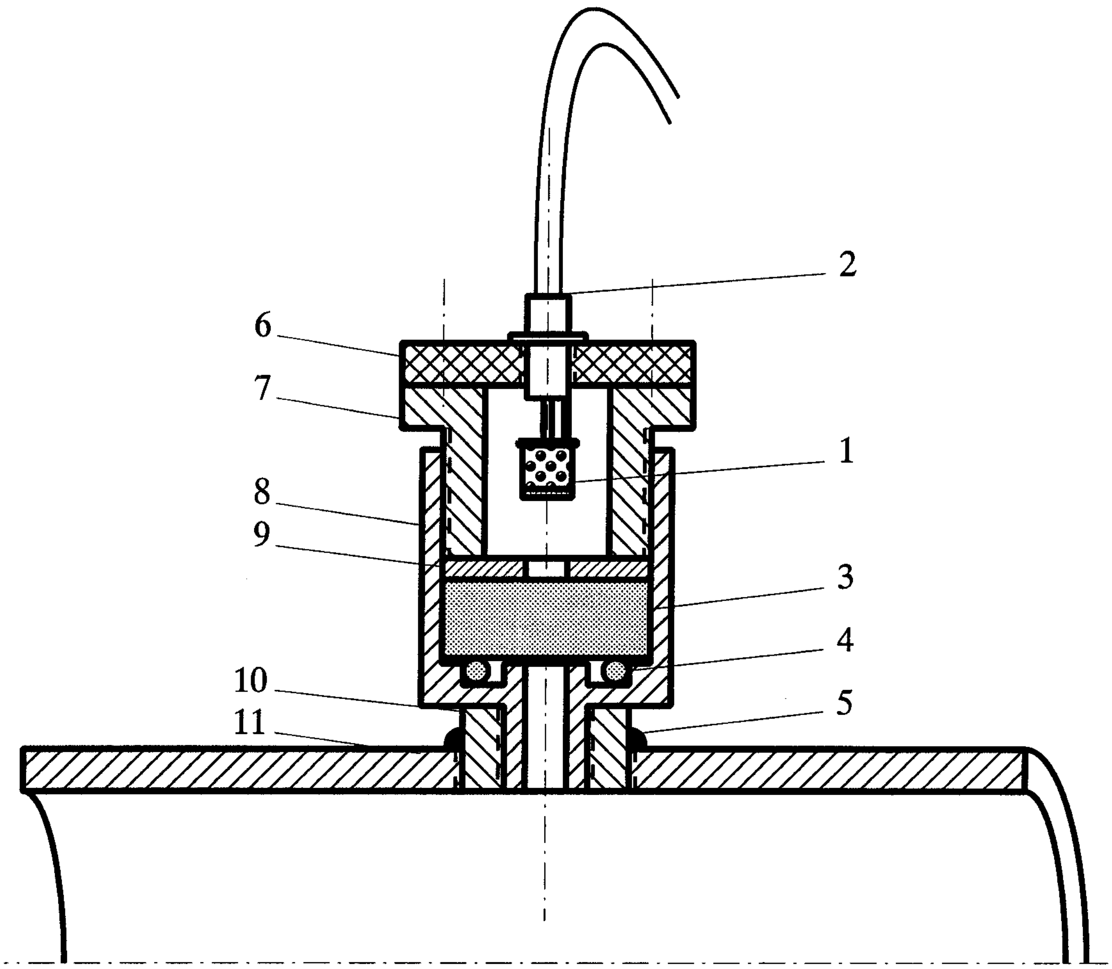
1 - DRIVER SECTION, 2 - TEST SECTION, 3 - GATE VALVE,
4 - FUEL, 5 - OXIDIZER, 6 - AGENT, 7 - METERING VALVE,
8 - ON-OFF VALVE, 9 - STATIC PRESSURE TRANSDUCER,
10 - DUAL CIRCULATION PUMP, 11 - VACUUM PUMP

Figure 3 Schematic of the detonation/deflagration tube gas handling system



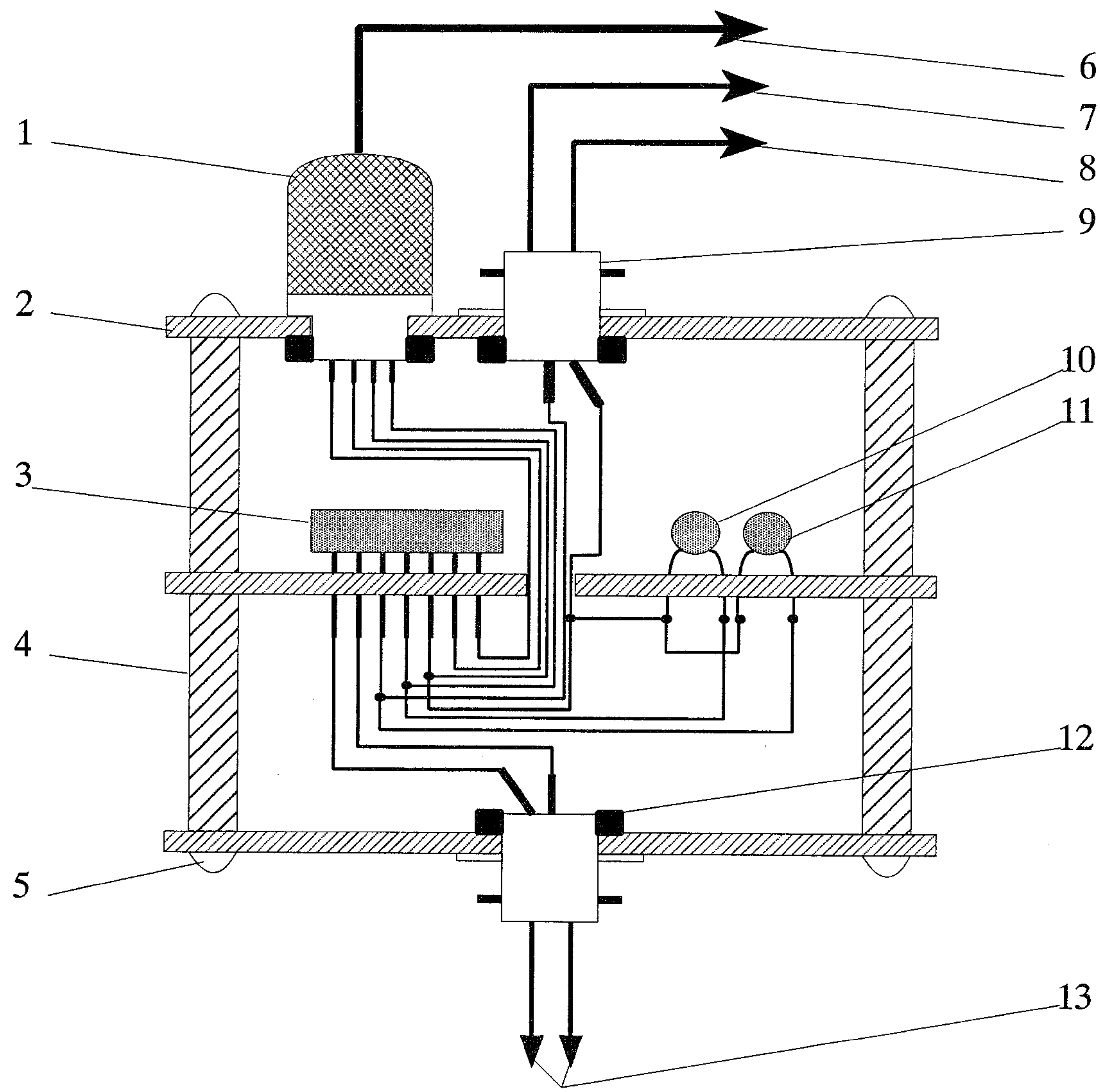
1 - LOW-NOISE CABLE, 2 - CABLE CONNECTOR, 3 - PIEZO-ELECTRIC PRESSURE TRANSDUCER, 4 - STUB, 5 - TUBE, 6 - RETAINING NUT, 7 - HOLDER, 8 - SEALS, 9 - SEAL WELD

Figure 4 Schematic of the piezo-electric dynamic pressure transducer mounting



1 - PHOTODIODE, 2 - BNC CABLE, 3 - QUARTZ WINDOW,
4 - "O" RING, 5 - SEAL WELD, 6 - COVER, 7 - BUSH, 8 - CASE
9 - WASHER, 10 - STUB, 11 - TUBE

Figure 5 Schematic of the fast photodiode mounting



1 - DIN CONNECTOR, 2 - CIRCUIT BOARD, 3 - OPERATIOANL AMPLIFIER, 4 - STANDOFF, 5 - SCREW, 6 - TO POWER SUPPLY, 7 - SIGNAL OUTPUT, 8 - GROUND, 9 - BNC CONNECTOR, 10, 11 - CAPACITORS, 12 - NUT, 13 - TO PHOTODIODE

Figure 6 Schematic of the fast photodiode amplifier

4. Experimental Results

4.1 Conditions. The following independent parameters were changed during the course of the experiments:

- type of suppressant (C_2HF_5, C_3F_8, and CF_3I);

- concentration of suppressant;

- type of fuel (ethene or propane);

- equivalence ratio of the combustible mixture (lean, stoichiometric, rich)

- geometry of the tube (2.5 or 5 m long test section, with or without spiral).

The initial temperature of the mixtures was ambient (22 ± 3 °C) and the initial pressure was 100 ± 0.6 kPa . The oxidizer used in all experiments was breathing grade air. Ethene and propane (CP grade 99.5% volume purity) were chosen as the fuels because it is known that subsonic flames, quasi-detonations, and full detonations all can be obtained in a tube of this geometry simply by varying the stoichiometry. The extinguishing compounds were used as supplied by the manufacturers.

In the case of ethene/air/suppressant mixtures, the spiral insert was always present in the 2.5 m long test section of the tube, and experimental results were obtained in the quasi-detonation regime of combustion. The flame and shock signals serving to determine velocities and pressures were taken 2.2 m downstream behind the gate valve.

In the case of propane/air/suppressant mixtures the 5 m test section was used without the spiral insert. The additional length was required to prevent the reflected shock wave from interfering with the slower moving primary reaction front. The experimental results were obtained in the high-speed and quasi-detonation regimes of combustion. The flame signals serving to determine velocities were taken 0.3 m downstream behind the gate valve. The shock signals serving to determine pressures were taken 2.2 m downstream behind the gate valve.

The partial pressure measurements were affected by the accuracy of the static pressure transducer (± 0.3 kPa after combining non-linearity, hysteresis, repeatability, and temperature effects), the accuracy of the digital display device (± 0.015 kPa), the accuracy associated with the purity of the gases (± 0.5 % of partial pressure reading), and the accuracy associated with possible gas losses in the circulation pump (up to 0.3 % of the partial pressure reading, in the worst case). Assuming that the errors are additive, the absolute partial pressure for any component in the mixture is accurate within 0.32 kPa plus 0.3 % of the reading.

4.2 Measurement Signals. Typical measurement signals are shown in Figures 7 and 8. Figure 7 shows signals coming from two fast photodiodes which represent radiation (peak response at 850 nm) associated with the reaction front traveling in the tube. Figure 8 displays signals from two piezoelectric pressure transducers which represent a pressure jump associated with the shock wave ahead of the primary reaction zone. The time difference between the occurrence of the signals allows one to determine flame and shock velocities. The amplitude of the pressure signals permits determination of the pressure ratio of the shock.

The accuracy of the determination of the shock wave amplitude was affected by the combined accuracy of the dynamic pressure transducer (± 1% of the reading), the combined accuracy of the

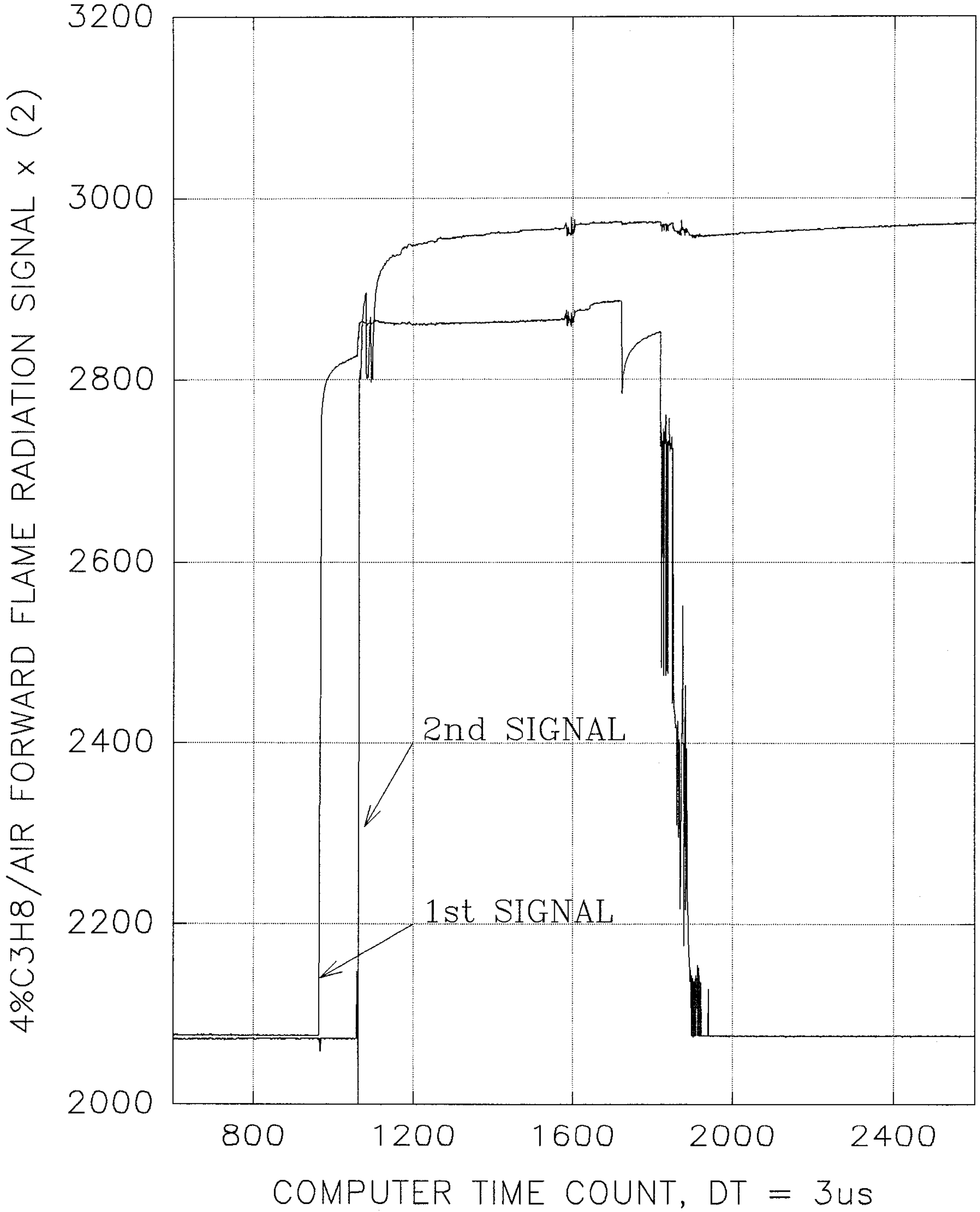


Figure 7 Typical measurement signals representing flame radiation detected by the photodiodes

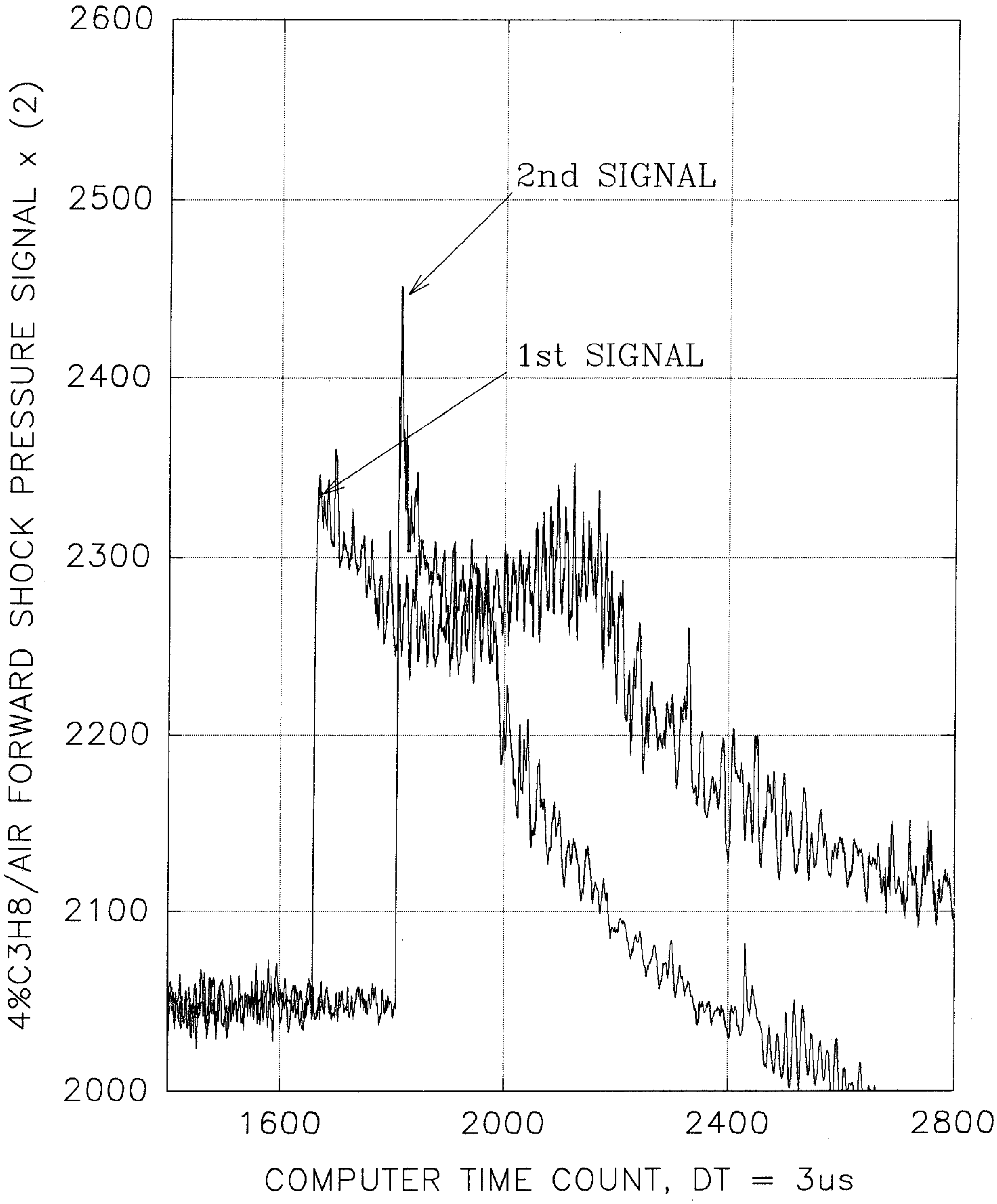


Figure 8 Typical measurement signals representing shock pressure detected by the dynamic pressure transducers

transducer amplifiers (± 0.5 % of the reading), the combined accuracy of the digital data acquisition system (± 0.5 %), and the combined accuracy of the digital readout device which (± 0.2 %). Assuming additivity of errors, the resultant accuracy of determining the shock wave amplitude is ± 2.2%. The uncertainty of the determination of the shock time differences was affected by the same elements, as well as the transducer rise time ($< 2\ \mu s$). The shock speed can thereby be estimated to be accurate to better than ± 4.4% of the reported reading (accounting for the differential nature of this measurement). The accuracy of the determination of the flame travel time was affected primarily by the rise time of the photodiode, which is 30 ns. The combined accuracy of the magnitude of the photodiode signal is estimated to be ± 2 % of the range.

4.3 Combustion Characteristics. The combustion generated in the driver section creates a shock wave followed by a chemically reacting region. The dependent parameters that were used to characterize the combustion within the test section of the tube are the pressure rise across the shock, the speed of the shock, and the speed of the chemically reacting radiation front. A secondary reaction was sometimes observed following the reflection of the incident shock wave from the end wall. The incident (or forward-travelling) shock wave speed and pressure ratio were determined from the piezoelectric transducer signals, and the time between activation of the photodiodes was used to calculate the forward-travelling radiation (or flame) front.

The repeatability of the measurements was affected by the following factors: preparation of the mixtures; circulation/homogenization of the mixtures; opening of the gate valve; the ignition parameters; formation/propagation of the flame/shock; vibrations of the spiral insert; and ambient temperature changes (ambient air pressure and humidity changes did not affect the results as air was supplied from a gas cylinder). Because each of these factors has an indeterminate randomness associated with it, a single test condition was repeated eleven times to quantify the precision of the experiment: a lean mixture of propane and air, with no suppressant in test section, and the 10 m long tube with no spiral in the test section. More than 20 replicates would have been required to produce a meaningful standard deviation as specified by Taylor and Kuyatt (1994); thus, in the present study the maximum, rather than standard, deviation is used to indicate the precision of the inferred results. The mean of the eleven tests and maximum absolute deviations are as follows:

flame speed, 334 ± 38 m/s; shock speed, 681 ± 25 m/s; and shock pressure ratio, 8.16 ± 0.38.

4.3.1 Ethene/Air Mixtures. Figure 9 shows the dependence of the forward shock wave velocity versus equivalence ratio of the ethene/air mixture for the two cases: with and without the spiral insert in the test section of the tube. The equivalence ratio was changed in such a way to cover the full range of various combustion/flammability modes detectable by the installed apparatus. It has been found that the shock wave generated by an accelerating flame is detectable for equivalence ratios between 0.5 and 2.12 for the two geometric configurations. The maximum shock velocity of nearly 2000 m/s was recorded for the situation without the spiral. In most cases (shock velocities higher than 500 m/s) the flame velocity was the same as the shock velocity.

Figure 10 displays the respective forward shock pressure ratios in the ethene/air mixture versus equivalence ratio for the two geometric configurations. Interestingly, the maximum pressure ratio of 35 was recorded for the situation with the spiral, which indicates clearly that transverse shock reflections from the wall play an important role in the whole process. However, in general, the shape of the pressure ratio curves corresponds well with the shape of the velocity curves.

Essentially, one can notice occurrence of four combustion modes:

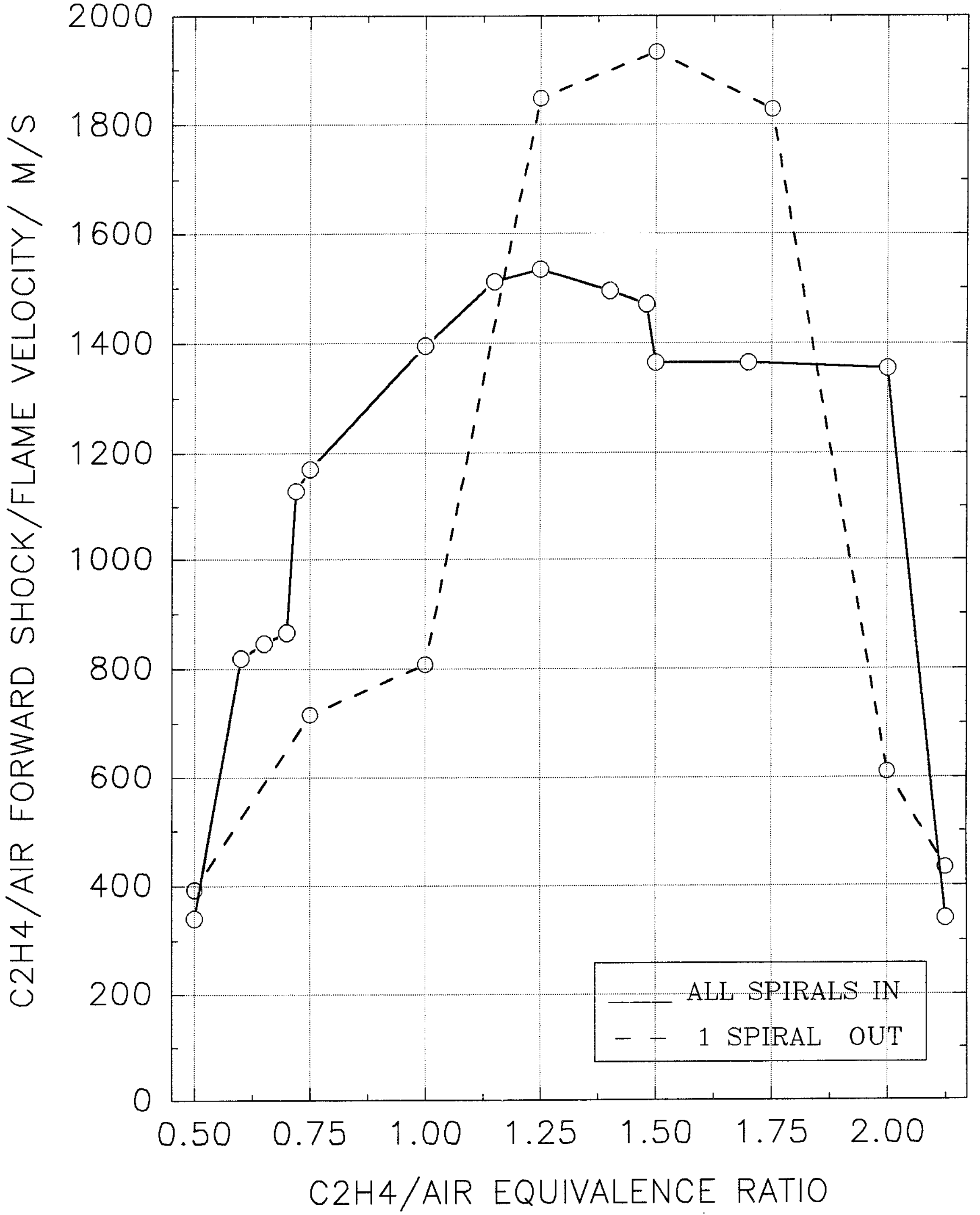


Figure 9 Combustion modes in the ethene/air mixtures - shock/flame velocities (2.5 m test section)

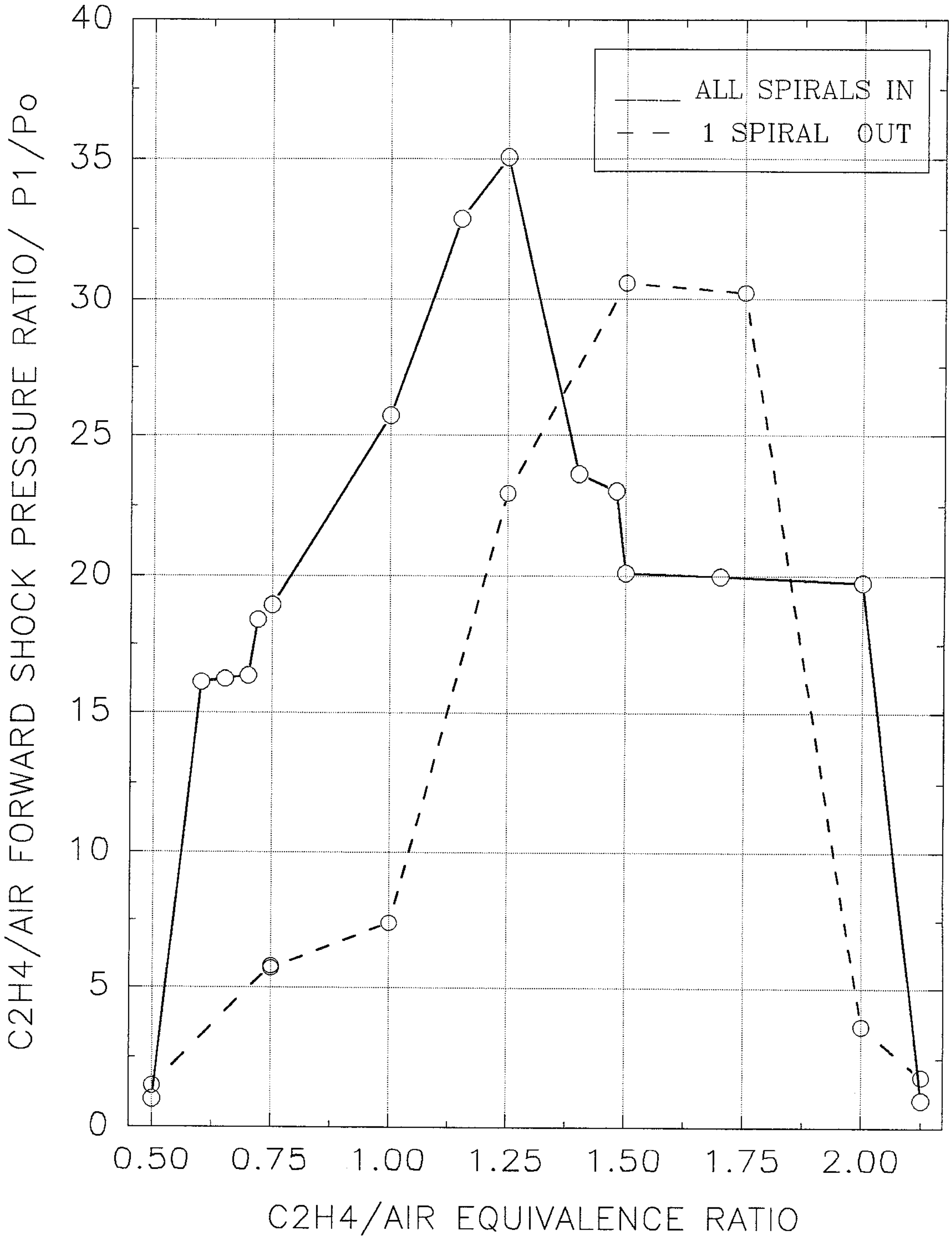


Figure 10 Combustion modes in the ethene/air mixtures - shock pressure ratios (2.5 m test section)

a. Low-speed deflagration generates a weak pressure wave in which the flame front is uncoupled. A typical pressure wave velocity is 400 m/s and pressure ratio is 1.5 for the two geometric configurations.

b. High-speed deflagration generates a strong pressure wave that is coupled with the flame front, the velocity of the flame is the same as the velocity of the pressure wave, and the shock-flame distance is on the order of centimeters. A typical velocity is 800 m/s and pressure ratio is 16 for the lean mixtures, and 1400 m/s and 20 for the rich mixtures, respectively, when the spiral insert is in the tube. When the spiral is not present in the tube the respective parameters are as follows: 700 m/s and 7 for the lean mixtures, and 600 m/s and 3 for the rich mixtures.

c. Quasi-detonation is associated with the occurrence of high velocities and pressure ratios; i.e., higher than in high-speed deflagrations. The flame front is coupled with the pressure wave, the velocity of the flame is the same as the velocity of the pressure wave, and the shock-flame distance is on the order of millimeters. Typical velocities are 1200 to 1500 m/s and pressure ratios are 20 to 35 over broad lean and rich ranges for the situation with the spiral insert in place. When the spiral is not present the transition from the high-speed deflagration mode to a detonation is gradual. The velocities and pressure ratios are significantly lower. This mode occurs on the rich side of the ethene/air mixture.

d. Chapman-Jouguet detonation occurs in the rich ethene/air mixture without the spiral insert, the flame front is coupled with the pressure wave, the velocity of the flame is the same as the velocity of the pressure wave, and the shock-flame distance is undetectable. A typical velocity is 1900 m/s and pressure ratio is 30. The velocity corresponds to the theoretical equilibrium thermodynamic estimates; however, the pressure ratios are 1/3 higher which may indicate the occurrence of an over-driven detonation mode.

4.3.2 Propane/Air Mixtures. Uninhibited propane/air mixtures were evaluated in the 2.5 m test section. Figure 11 shows the dependence of the forward shock wave velocity versus equivalence ratio. As it was for the ethene/air mixture, the equivalence ratio was changed in such a way to cover the full range of various combustion/flammability modes detectable by the apparatus. It was found that the shock wave generated by an accelerating flame was detectable for equivalence ratios between 0.65 and 1.45 for the two geometric configurations. A maximum shock velocity of nearly 1300 m/s was recorded for the situation with the spiral, which differs significantly from the situation for the ethene/air mixture. Here also the flame velocity was the same as the shock velocity, but only for velocities above 800 m/s.

Figure 12 displays the respective forward shock pressure ratios in the propane/air mixture versus equivalence ratio for the two geometric configurations. Here the maximum pressure ratio of 27 corresponds to the maximum velocity for the situation with the spiral. In general, the shape of the pressure ratio curves corresponds closely to the shape of the velocity curves.

The analysis of the curves leads to the identification of three combustion modes:

a. Low-speed deflagration generates a weak pressure wave, with the flame front uncoupled. Typical pressure wave velocities are 400 to 600 m/s and pressure ratios are 1.5 to 3 for the two configurations.

b. High-speed deflagration generates a strong pressure wave coupled to the flame front, the velocity of the flame is the same as the velocity of the pressure wave, and the shock-flame

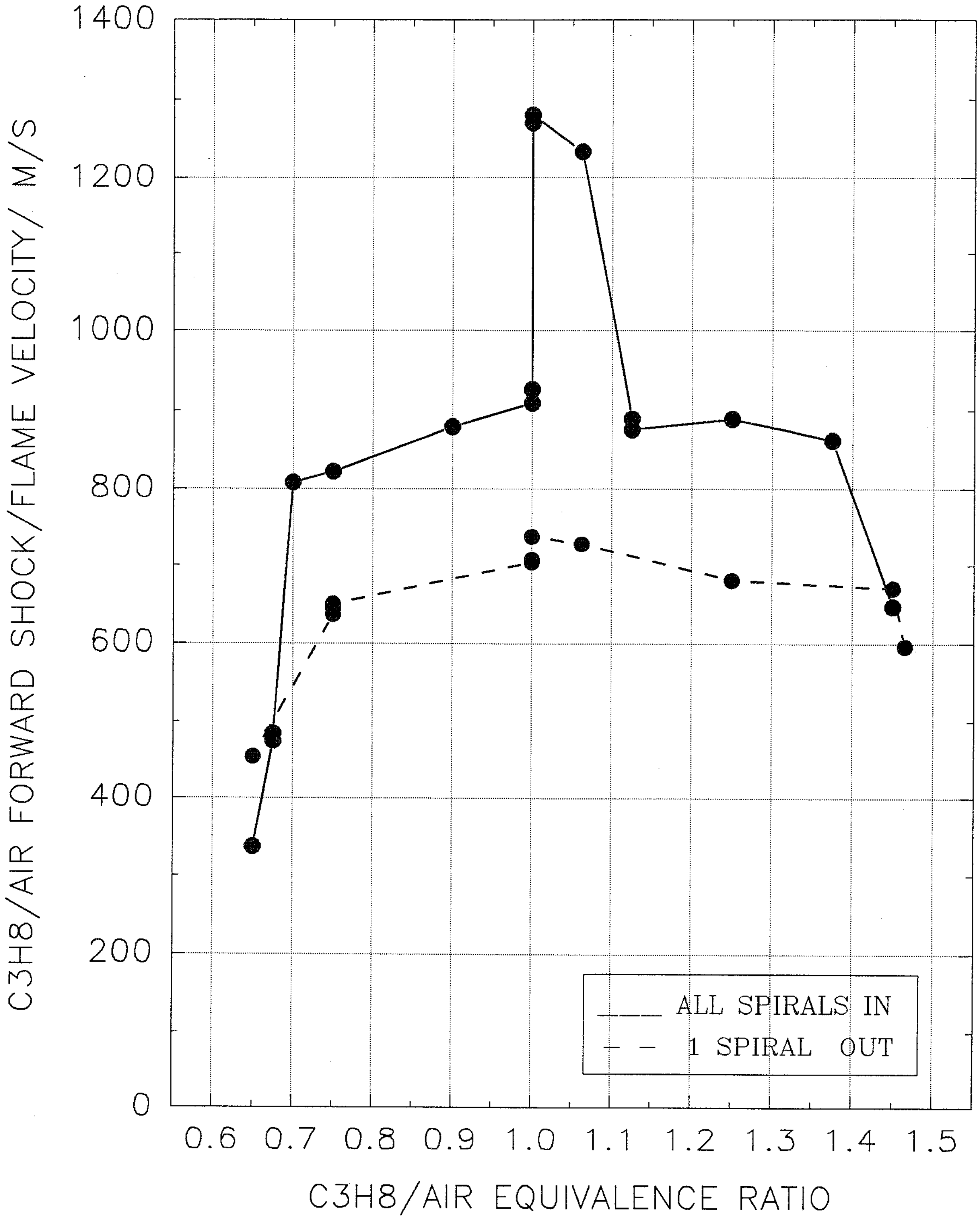


Figure 11 Combustion modes in the propane/air mixtures - shock/flame velocities (2.5 m test sect.)

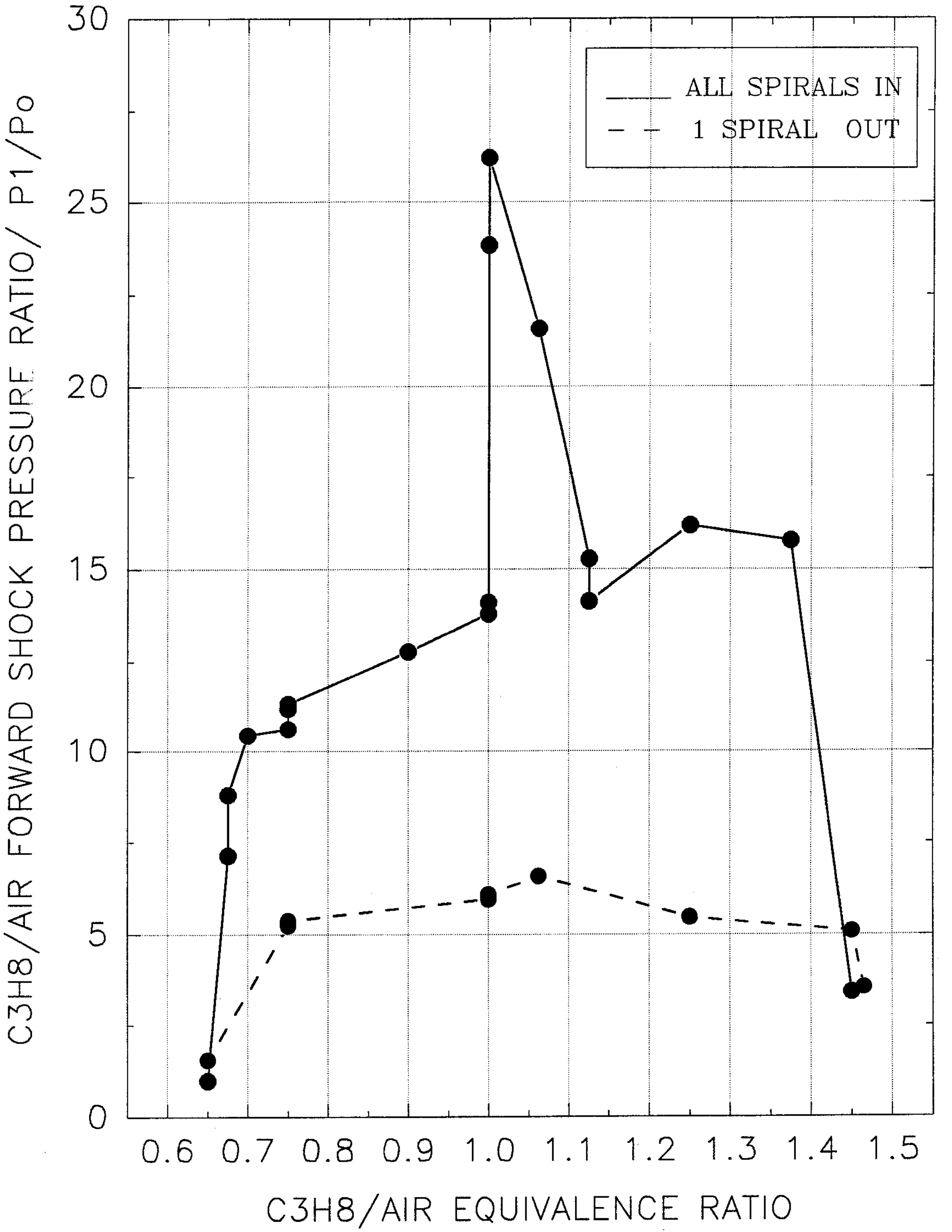


Figure 12 Combustion modes in the propane/air mixtures - shock pressure ratios (2.5 m test section)

distance is on the order of centimeters. Typical velocities are 800 to 900 m/s and pressure ratios are 11 to 14 for the lean mixtures, and 900 m/s and 15 for the rich mixtures, respectively, when the spiral insert is in the tube. When the spiral is not present the velocity and pressure ratio are 650 m/s and 6 for the lean and rich mixtures.

c. Quasi-detonation is associated with the occurrence of significantly higher velocity and pressure ratio, with the flame front coupled with the pressure wave, the velocity of the flame is the same as the velocity of the pressure wave, and the shock-flame distance is on the order of millimeters. A typical velocity is 1250 m/s and pressure ratio is 25 in the narrow rich neighborhood of the stoichiometric composition for the situation with the spiral. When the spiral is not present in the tube, the quasi-detonation regime of combustion disappears: the velocities and pressure ratios at the same fuel concentrations are only slightly higher than in the high-speed regime.

There is a significant difference in combustion behavior between propane/air and ethene/air mixtures: the combustion modes at higher velocities overlap totally in the ethene/air mixture for the two geometric configurations, while the propane/air mixture is characterized by a clear separation between the combustion modes for the two arrangements. Also, the regime of equivalence ratios for which combustion is detectable in the tube is much broader for the ethene/air mixture. Furthermore, the detonation process is unable to develop in the propane/air mixture when the spiral insert is missing from the tube. Additionally, it is noteworthy that for the first time the quasi-detonation regime of combustion in the propane/air mixture has been recorded in the presence of the spiral obstacle. This finding extends the results of Lee (1984) and Peraldi et al. (1986).

4.4 Suppression Characteristics. The performance of the three extinguishing compounds (C_2HF_5, C_3F_8, and CF_3I) are analyzed by comparing the velocity and pressure ratio suppression characteristics in the lean, stoichiometric, and rich ethene/air and propane/air mixtures. The term "PHI" in Figures 13 through 36 denotes the fuel/air equivalence ratio calculated by ignoring the contribution of the agent to the fuel. The experimental points at a partial pressure of zero represent the reference states when no extinguishing compound was present in the test section of the tube. The points at the highest concentration for each suppression curve relate to full flame extinguishment. These data can be compared to the following results from experiments performed with 100% N_2 in the test section:

Mixture	Pressure Ratio	Shock Speed	Flame Speed
lean ethene/air/N_2	2.5	440 m/s	0 m/s
stoich. ethene/air/N_2	3.5	450 m/s	0 m/s
lean propane/air/N_2	4.5	590 m/s	50 m/s
stoich. propane/air/N_2	4.6	620 m/s	100 m/s
rich propane/air/N_2	4.5	595 m/s	100 m/s

Note that no measurements were taken with 100% N_2 in the test section and a rich ethene/air mixture. Also, the suppression experiments with propane/air mixtures were performed using the 5 m test section with no spiral insert.

4.4.1 C_2HF_5 Performance. Figure 13 shows that the velocity of the ethene/air shock/flame system essentially decreases with the increasing concentration of the compound. The exception is for the stoichiometric mixture where the velocity slightly increases at 3% by volume (or partial pressure fraction) of the suppressant. The velocity of the flame is the same as the velocity of the shock wave.

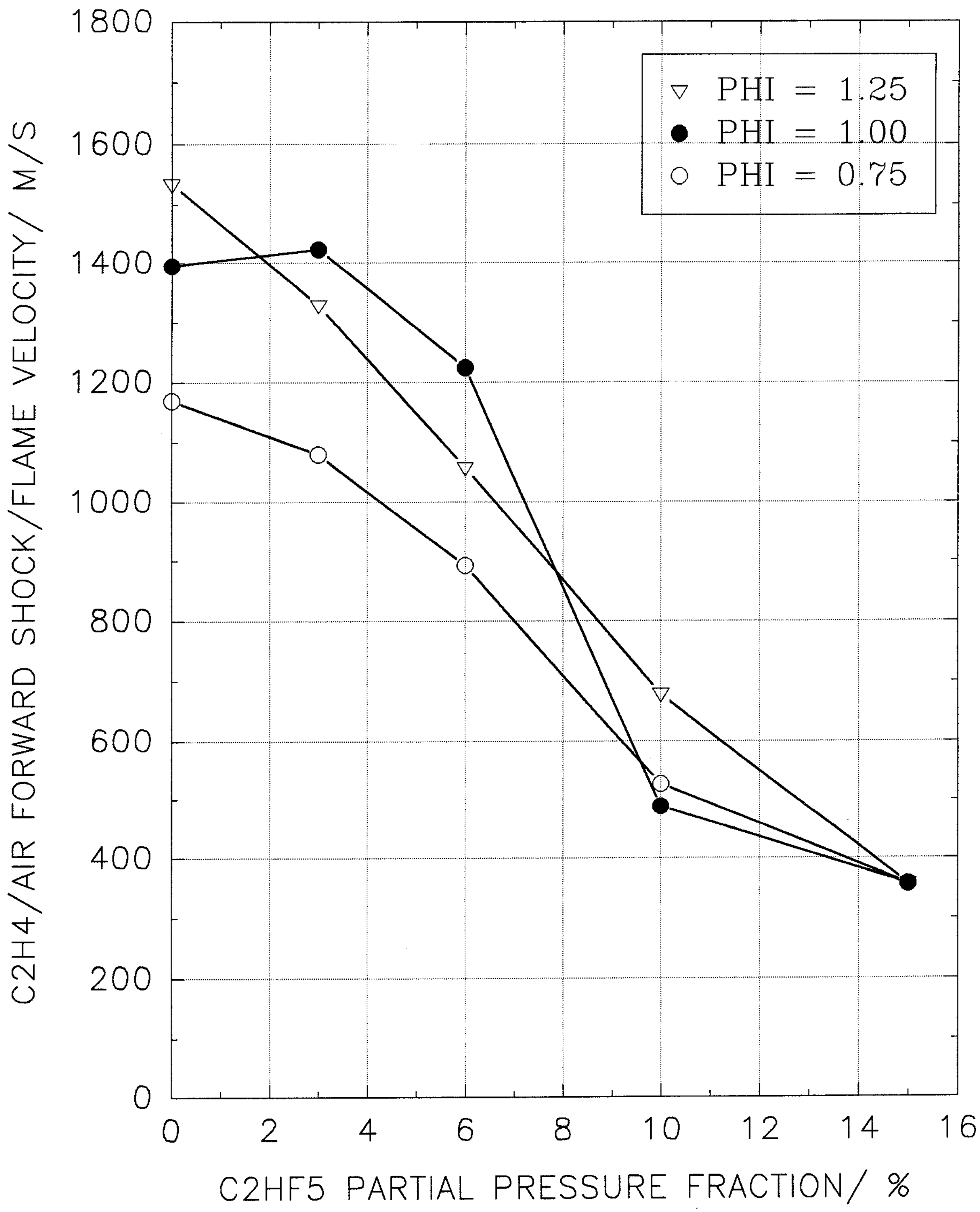


Figure 13 C_2HF_5 shock/flame velocity suppression performance in the ethene/air mixtures

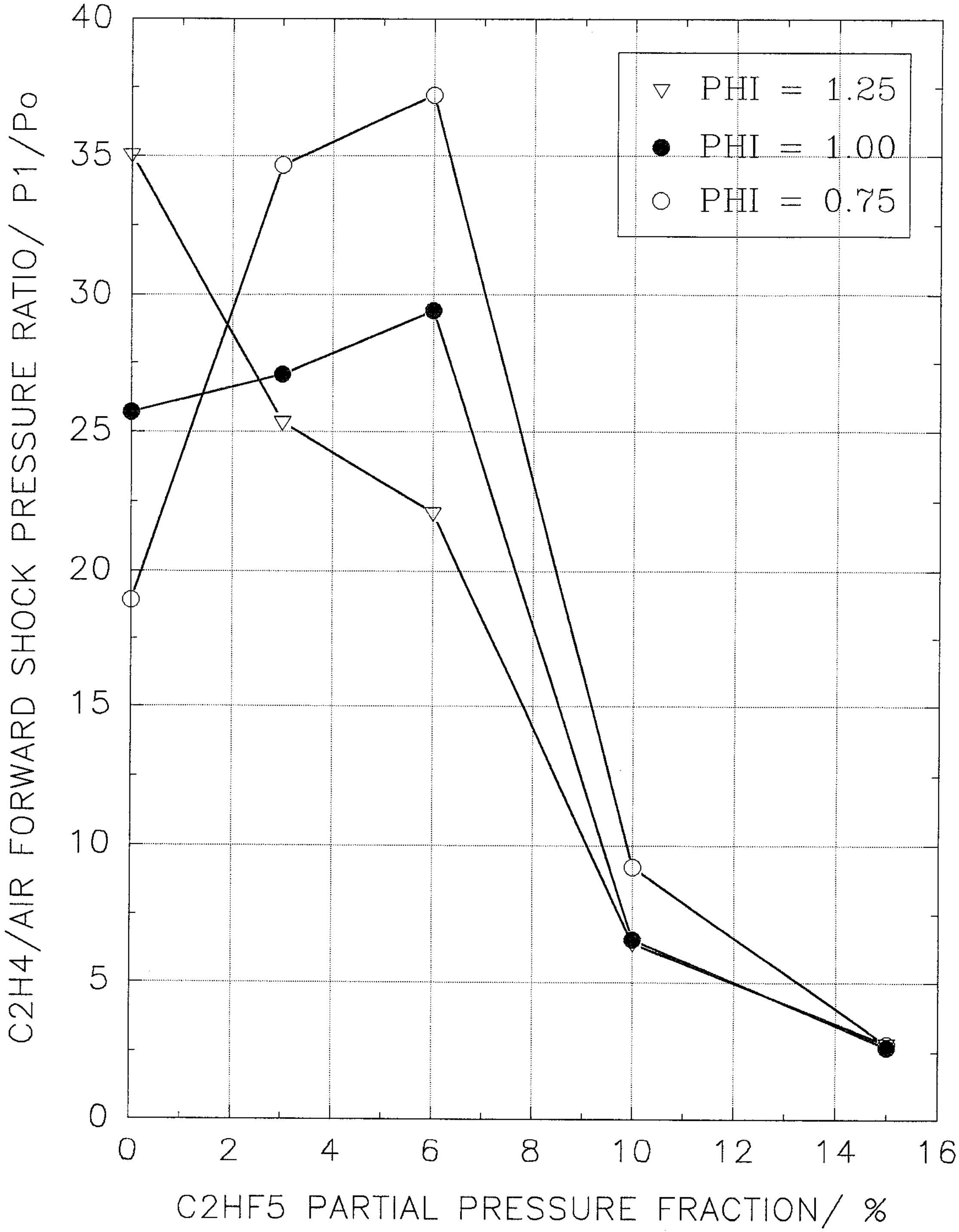


Figure 14 C_2HF_5 shock pressure ratio suppression performance in the ethene/air mixtures

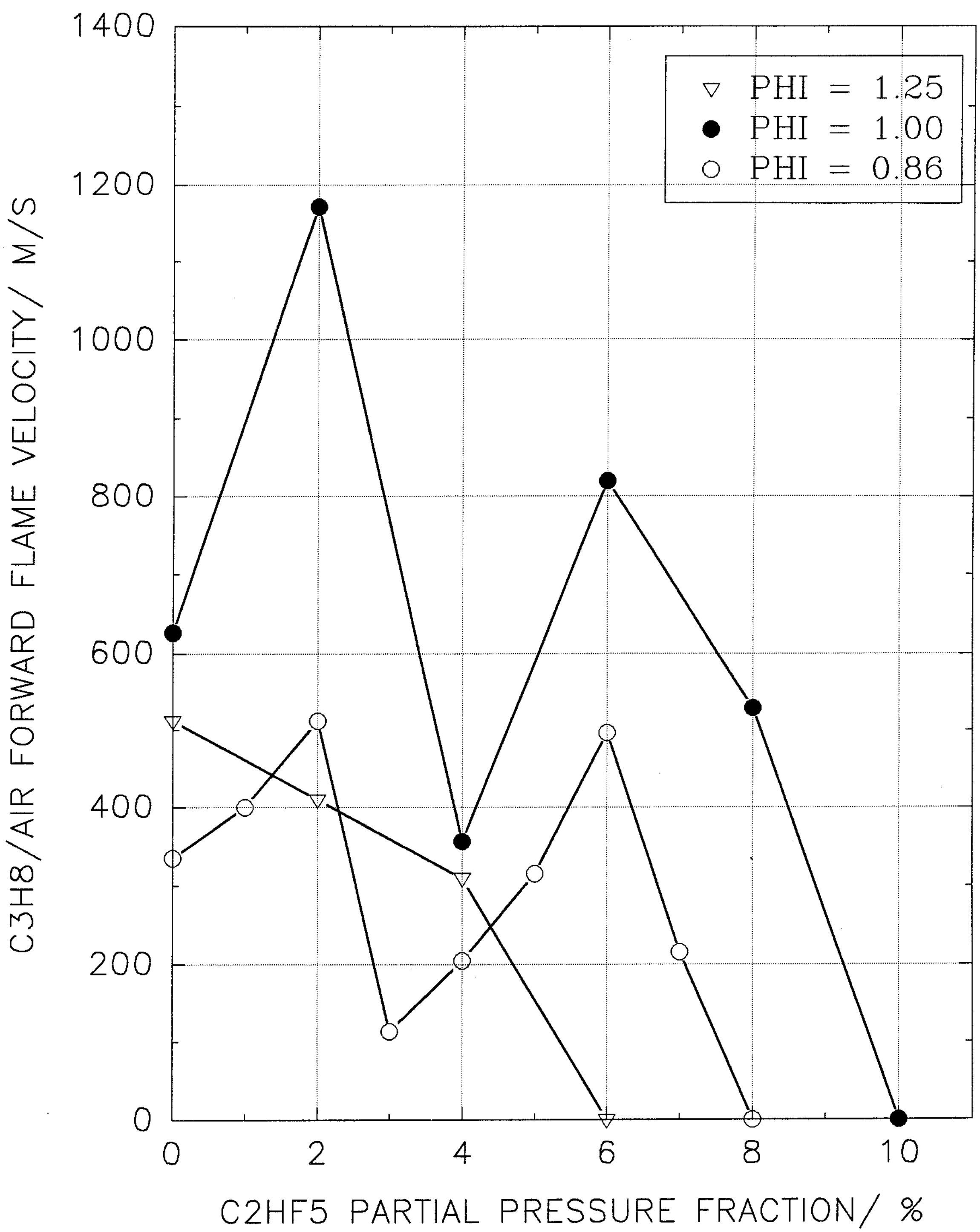


Figure 15 C_2HF_5 flame velocity suppression performance in the propane/air mixtures

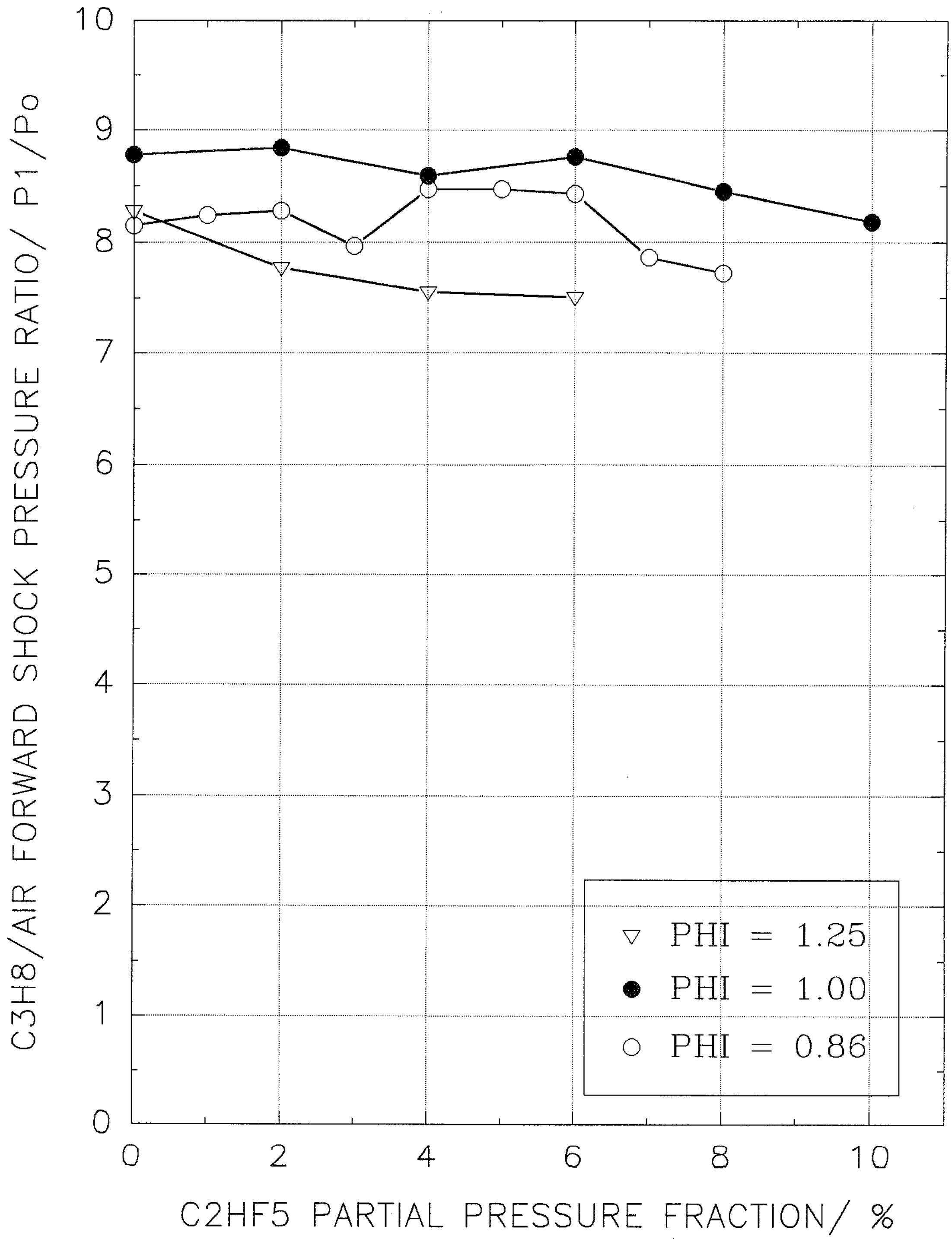


Figure 16 C_2HF_5 shock pressure ratio suppression performance in the propane/air mixtures

However, the distance between the shock and flame increases with the amount of the agent. The extinguishing partial pressure fraction is 15% for all the equivalence ratios.

Figure 14 displays the respective shock pressure ratios in the ethene/air mixture. The addition of the agent at the lower concentrations causes the pressure ratio to be doubled for the lean mixture. At agent levels between 0 and 8%, the pressure ratio is higher than that for the pure combustible mixtures. However, at the higher concentrations the pressure ratio drops dramatically. For the stoichiometric mixture, the trend appears similar, but to a much lesser extent. The situation is quite different for the rich mixture where the addition of the compound causes a systematic drop in the pressure ratio. At the point of extinguishment, in which the flame disappears, the pressure ratio is about 3 for all three equivalence ratios. Such behavior may be associated with the fact that when the agent contains a combustible component such as hydrogen it may enhance the heat release. Therefore, there are two competing processes: promotion of oxidation, and inhibition. The shape of the curves reflects that competition. The promotion effect does not occur in the rich mixture because the presence of hydrogen in the agent causes it to behave as a richer mixture.

Figure 15 exhibits the dependence of the flame velocity of the propane/air flame versus agent concentration just behind the gate valve. The results describe the flame behavior on the first contact with the extinguishing compound. One can see that the flame velocity strongly depends on the agent concentration and composition of the combustible mixture. There are two maxima and one minimum in the suppression curves for the lean and stoichiometric mixtures. This unexpected, non-monotonic behavior of flame velocity with increasing agent partial pressure is much larger than the uncertainty in the measured values. At small concentrations up to 2%, the flame is strongly enhanced (even up to 1200 m/s for the stoichiometric mixture). At 3 to 4%, the flame is suppressed to some extent, but at 6% the flame is again enhanced. Eventually, the increase in concentration causes the flame to be extinguished. Such a situation does not occur for the rich mixture, where the flame is suppressed systematically with increasing agent partial pressure. The extinguishing concentration depends on the equivalence ratio of the combustible mixture. The highest value, 10%, is for the stoichiometric mixture, and lower values of 8 and 6% are for the lean and rich mixtures, respectively.

Figure 16 demonstrates the impact of the agent on the shock pressure ratio far from the gate valve. These results indicate that the thermodynamics of the compound decomposition process is of significant importance for the pressure ratio, as the estimated temperature behind the forward shock may approach 1000 K depending on the shock Mach number. One can see that regardless of the agent concentration, the pressure is approximately constant with the exception of the rich mixture, where the pressure ratio drops more clearly. This may indicate that the endothermicity of the fuel decomposition is beginning to play a discernible role.

4.4.2 C_3F_8 Performance. Figure 17 shows that the velocity of the shock/flame system in the ethene/air mixtures decreases with the increasing amount of the agent in the test section of the tube. The trend is slightly different for the lean mixture, where at the low concentration the velocity increases slightly. However, the shape of the curves is about the same regardless of the composition of the combustible mixtures. This indicates that the curves are simply shifted relative to one another. The extinguishing level is 10% for all the equivalence ratios.

Figure 18 displays the respective shock pressure ratios in the ethene/air mixture. One can see a significant increase in the pressure ratio for the lean and stoichiometric mixtures at low agent concentration, and a slight increase for the rich mixture. As the concentration increases, the pressure ratios drop systematically until the extinguishing partial pressure fraction is reached at 3 to 4%. Here, there is also a shift in the curves when the equivalence ratio is changed, as observed for the velocity characteristics.

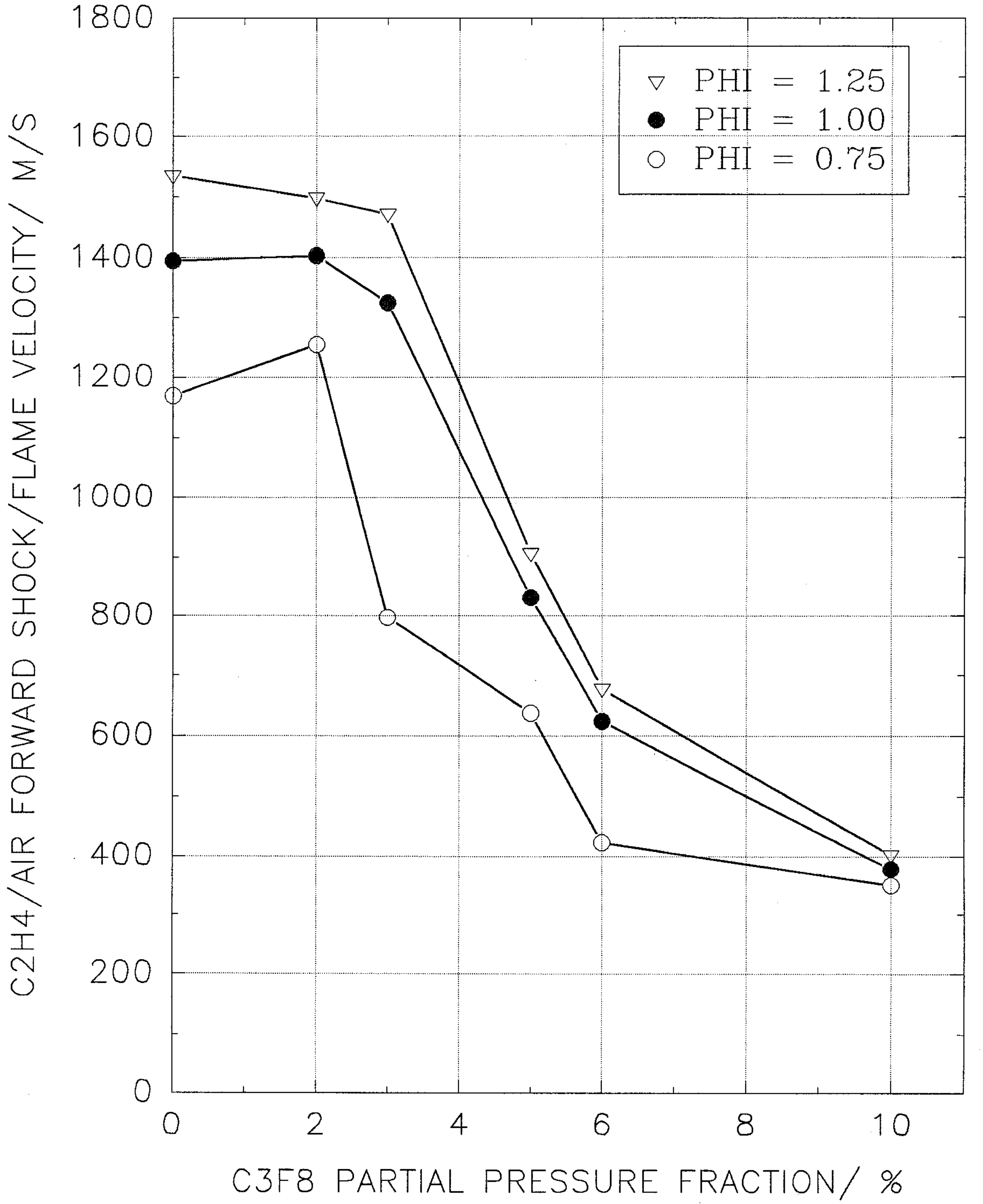


Figure 17 C_3F_8 shock/flame velocity suppression performance in the ethene/air mixtures

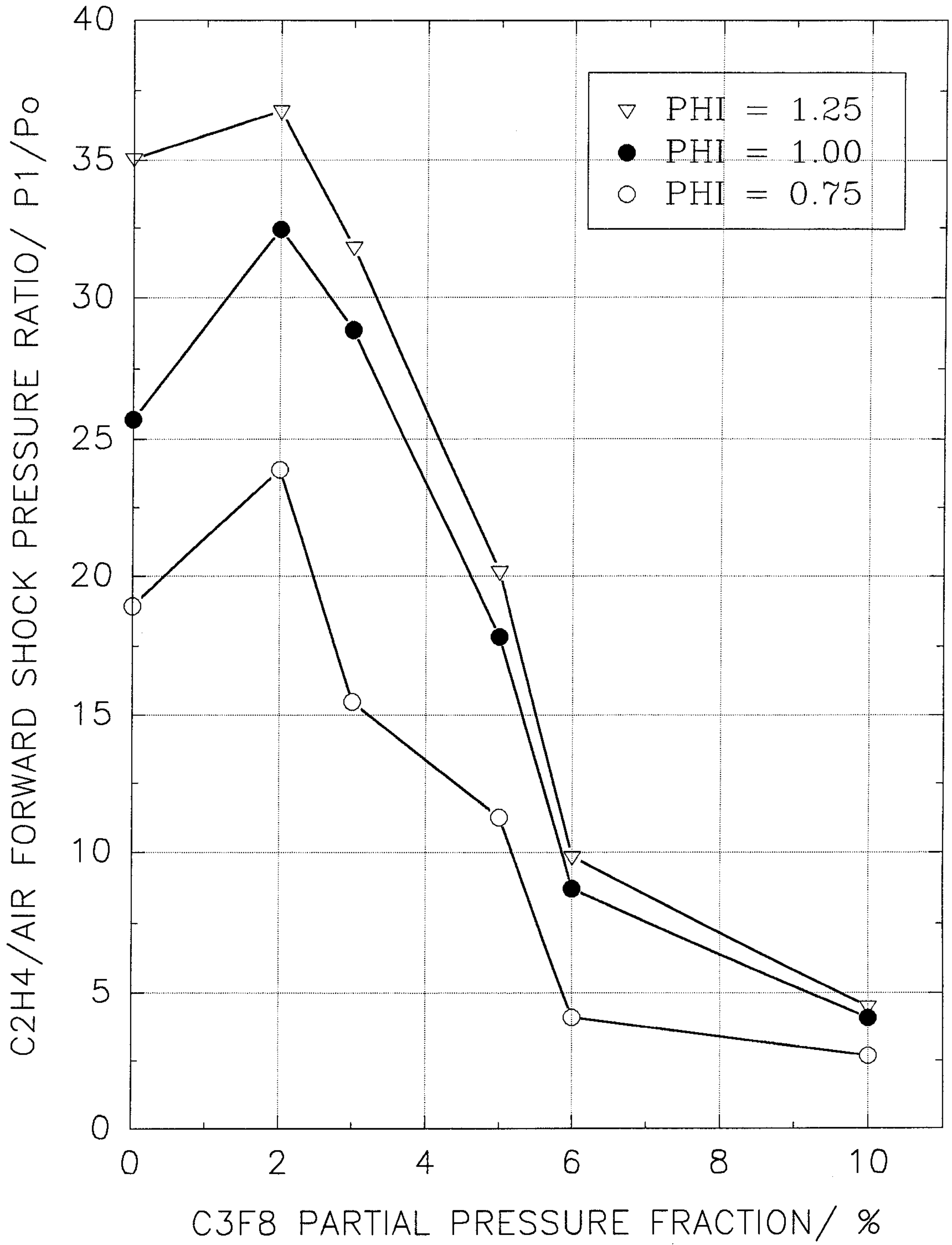


Figure 18 C_3F_8 shock pressure ratio suppression performance in the ethene/air mixtures

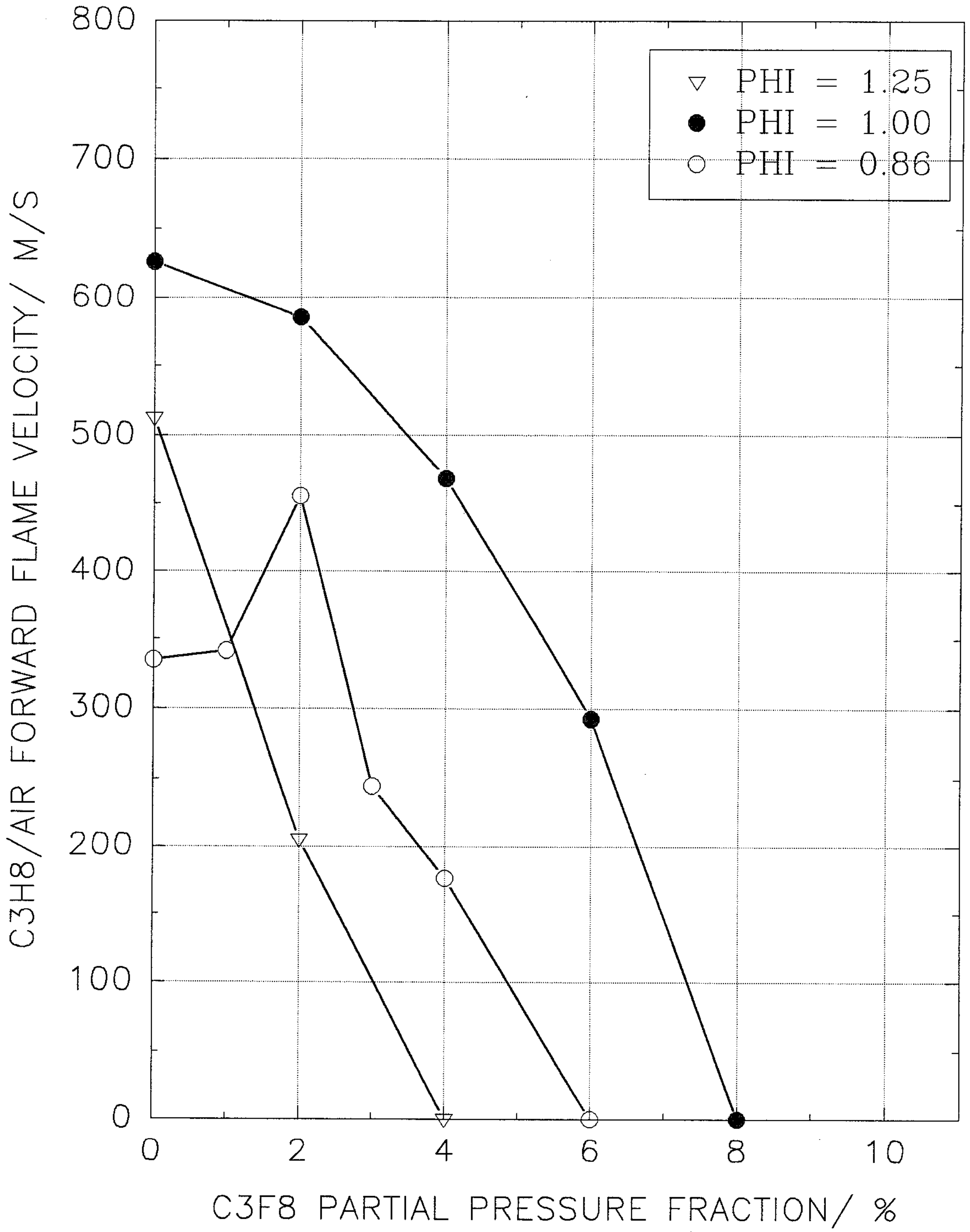


Figure 19 C_3F_8 flame velocity suppression performance in the propane/air mixtures

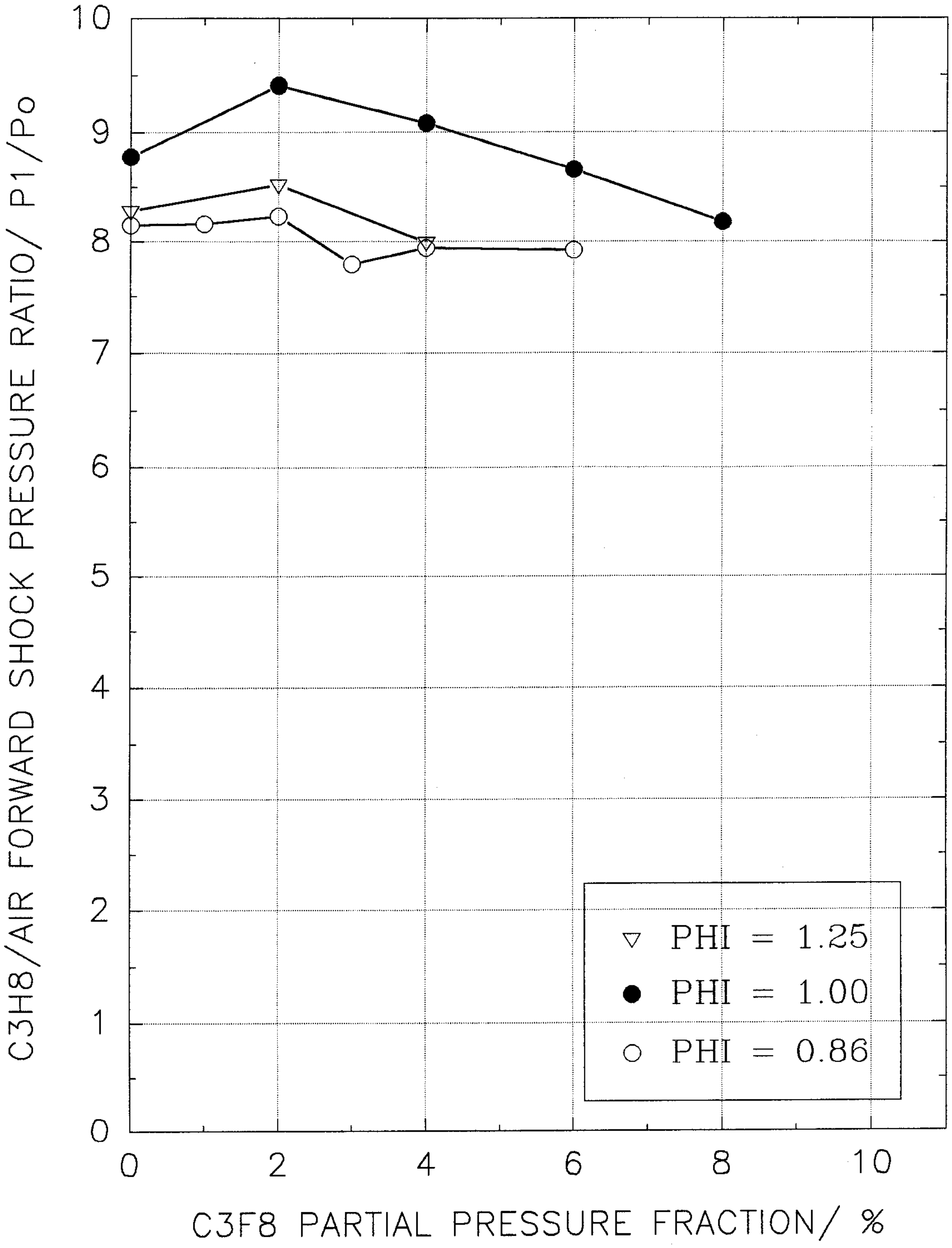


Figure 20 C_3F_8 shock pressure ratio suppression performance in the propane/air mixtures

Figure 19 indicates that the addition of the agent essentially decreases the flame velocity in the propane/air mixture. However, for the lean mixture, there is a significant increase in the velocity at small agent concentrations. The stoichiometric mixture is the most difficult situation in which to extinguish the flame and requires the highest agent concentration (8%). The easiest situation for extinguishment occurs for the rich mixture with an extinguishing level of 4%. The lean mixture requires 6% agent.

Figure 20 demonstrates the shock pressure ratios in the propane/air mixture. One can see that the pressure ratio slightly increases at low agent concentrations for all the compositions of the combustible mixture. At higher concentrations, there is a slight decrease, especially for the stoichiometric mixture in which it is clearly monotonic. Also, there is a local minimum at 3% for the lean mixture. Such changes are associated most probably with the thermodynamic effects (heat release or absorption) as the shock wave passes through the mixture.

4.4.3 CF_3I Performance. Figure 21 shows the complex behavior of the shock/flame velocity when the agent is added to the ethene/air mixture. At partial pressure fractions up to 4%, regardless of the composition of the combustible mixture, the velocity drops dramatically to between 500 and 1100 m/s depending on the equivalence ratio. At higher concentrations, between 4 and 6%, there is a reversal in the shock/flame velocity. Eventually, 10 to 12% of the agent causes extinguishment. The shape of the curves is almost identical regardless of the equivalence ratio of the combustible mixture. The reversal at higher concentrations may be due to recombination reactions, weakening the suppression effect mainly of the iodine atoms and also the CF_3 radicals.

Figure 22 displays the respective shock pressure ratios in the ethene/air mixtures. Qualitatively, the behavior of the suppression curves is nearly identical to those representing velocities. The quantitative difference is that at 6% the reversal gives even higher values of the pressure ratios than for the pure combustible mixture.

Figure 23 exhibits the complex behavior of the flame velocity in the propane/air mixture when the agent is added to the test section of the tube. At 1% agent partial pressure fraction the combustion process is significantly enhanced for all the equivalence ratios of the combustible mixture. At 2%, the combustion process is dramatically suppressed. However, at higher concentrations the combustion process recovers with the exception of the rich mixture. Eventually, extinguishment occurs at 14% by volume for the stoichiometric mixture, as well as 6 and 8% for the lean and rich mixtures, respectively. This shows that the stoichiometric propane/air mixture is the most difficult to extinguish with this compound.

Figure 24 demonstrates the shock pressure ratios in the propane/air mixtures with the agent added. The systematic drop in pressure ratio is very clear regardless of the composition of the combustible mixture. At extinguishment the typical values are between 5 and 6. The most likely reason for such a significant drop is the endothermicity of the decomposition process of the agent when the shock passes through the mixture. Interestingly, there are also local minima in the shock pressure ratios for all the equivalence ratios of the combustible mixtures.

The precision of the CF_3I suppression measurements were checked by repeating an experiment four times under the following conditions: 8% CF_3I in stoichiometric ethene/air mixture in the absence of the spiral insert. The mean values of the flame speed, shock speed and pressure ratio were found to be 1483 m/s, 1635 m/s and 32.57, respectively. The maximum absolute deviations of flame and shock velocities and pressure ratio were 157 m/s, 15 m/s and 0.97 respectively. This level of precision provides confidence that the trends observed in all the experimental sequences are real and meaningful.

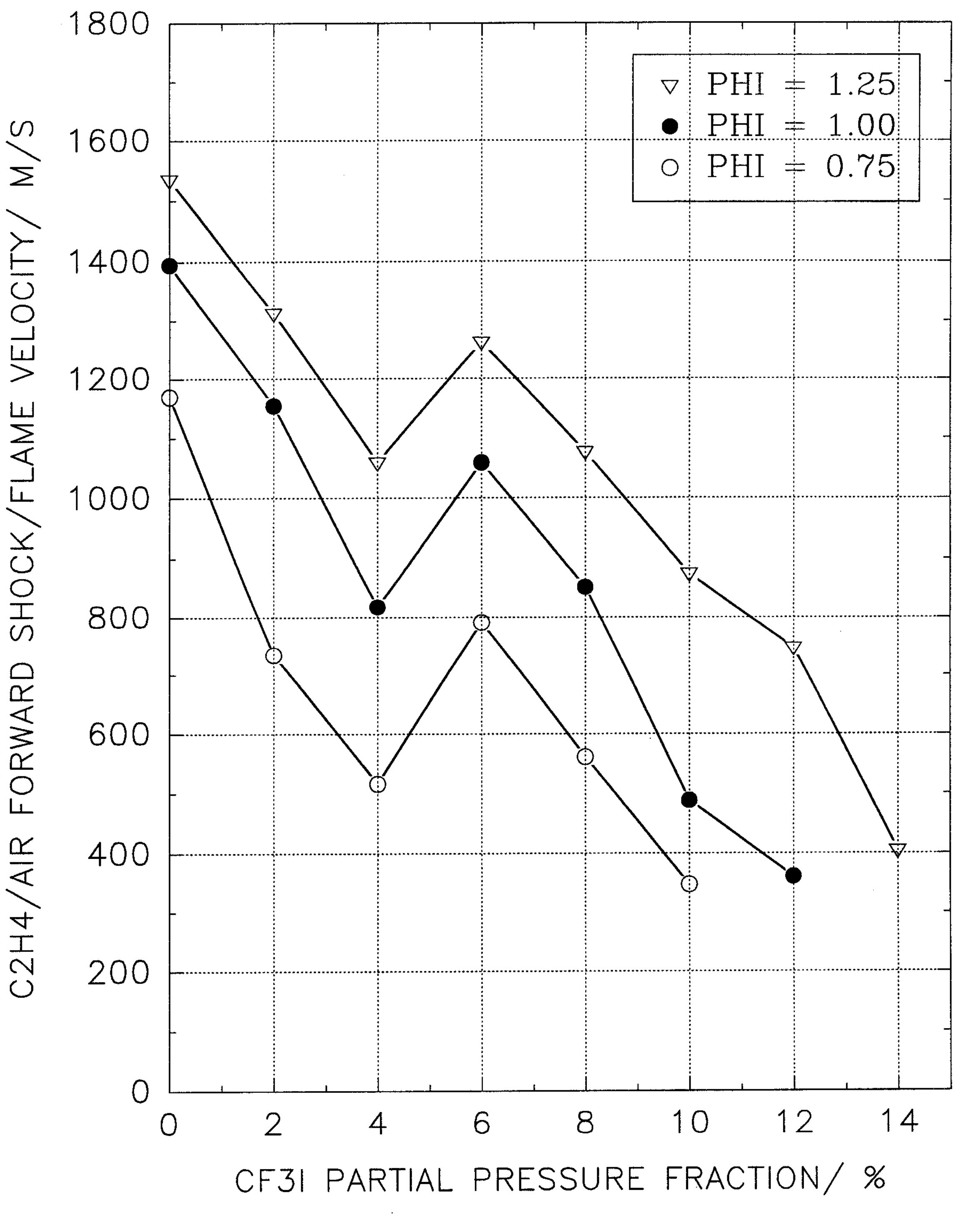


Figure 21 CF_3I shock/flame velocity suppression performance in the ethene/air mixture

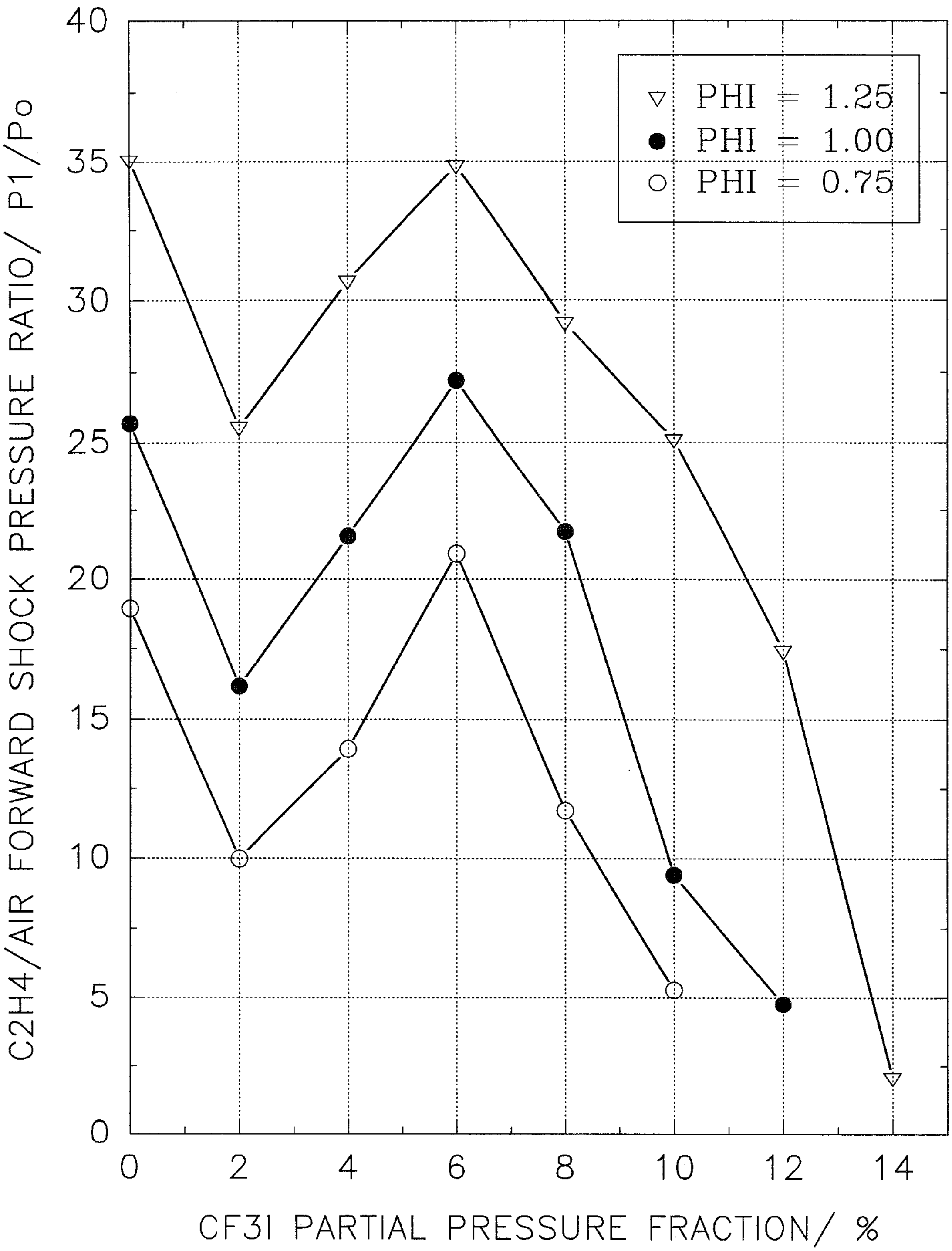


Figure 22 CF_3I shock pressure ratio suppression performance in the ethene/air mixture

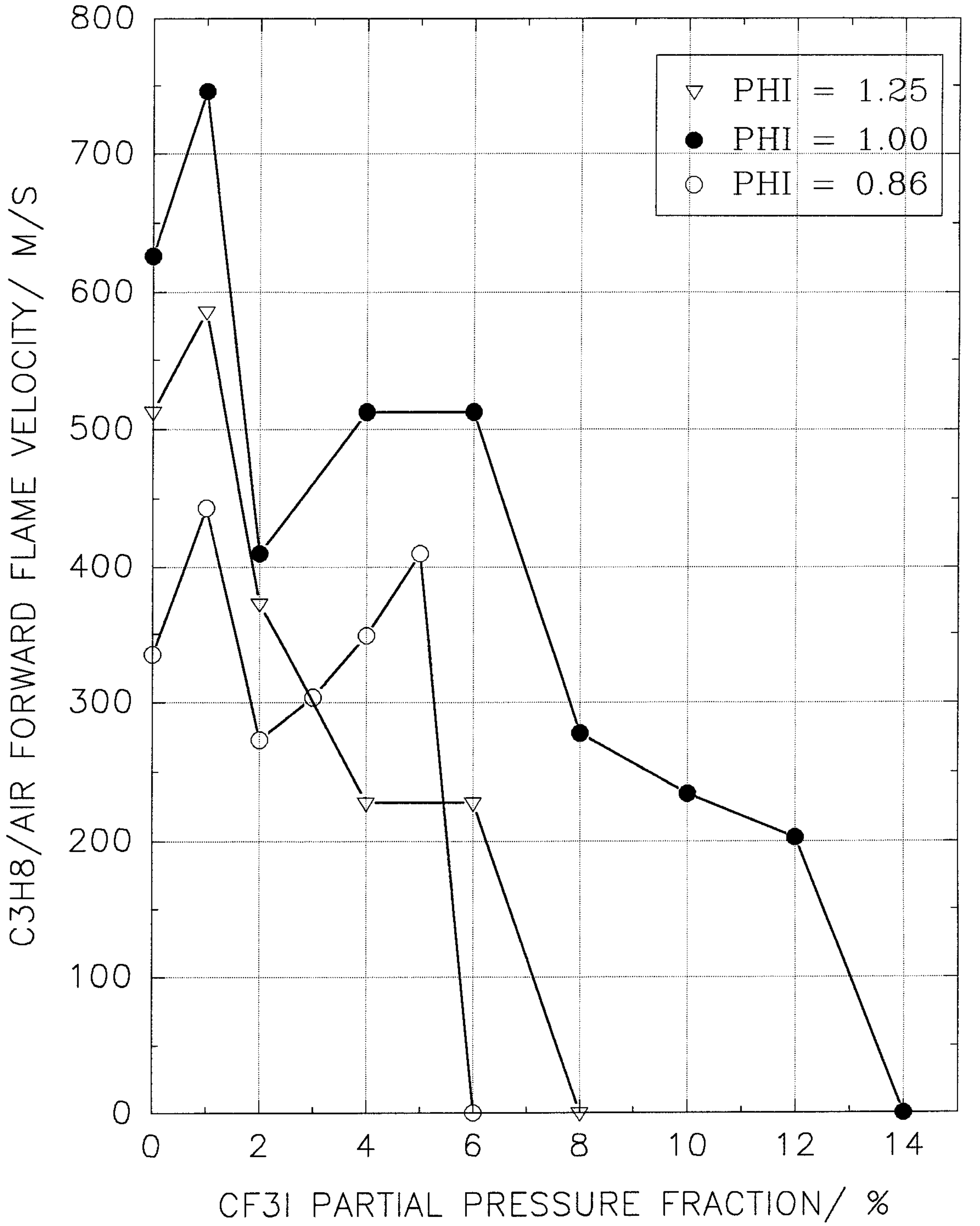


Figure 23 CF_3I flame velocity suppression performance in the propane/air mixture

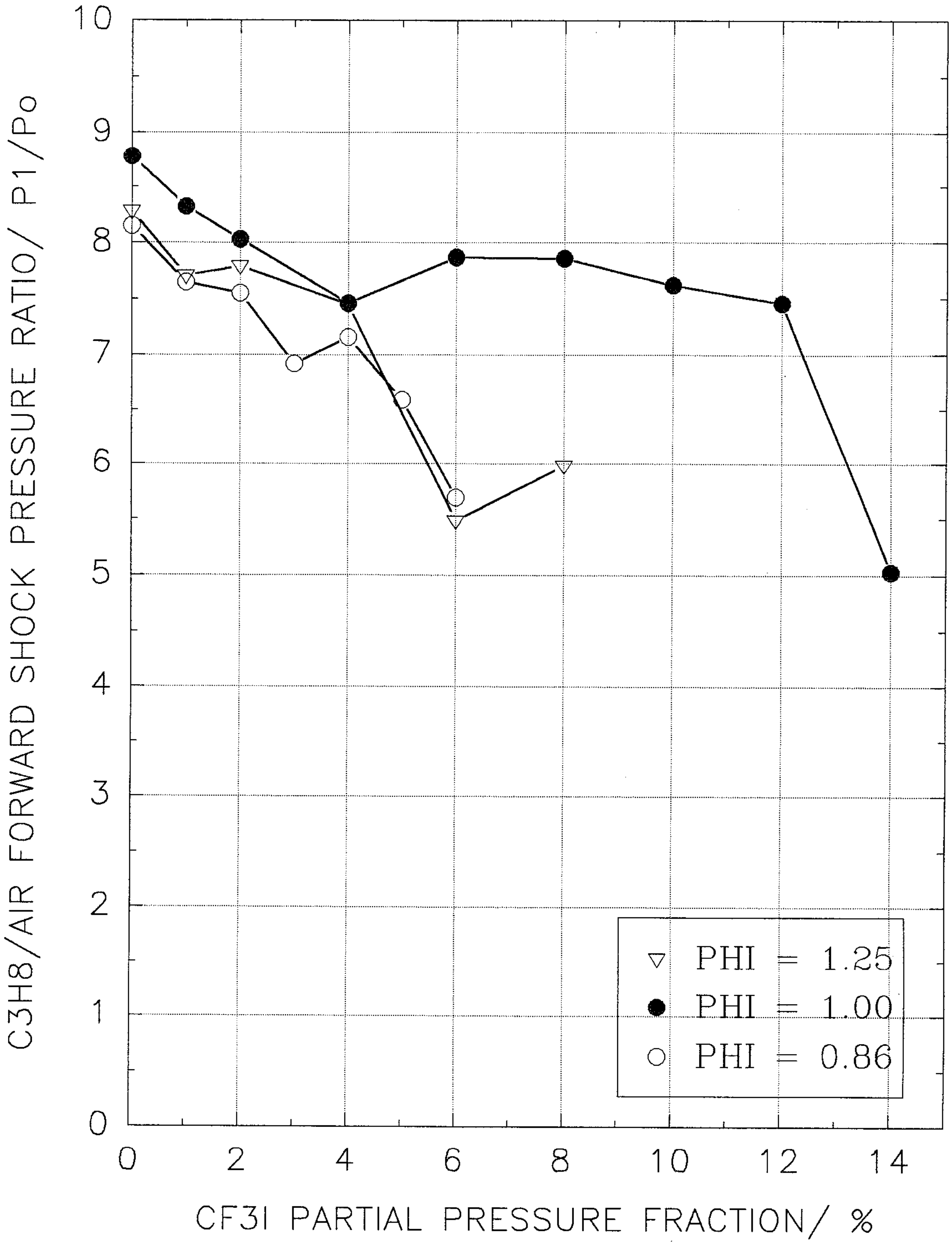


Figure 24 CF_3I shock pressure ratio suppression performance in the propane/air mixtures

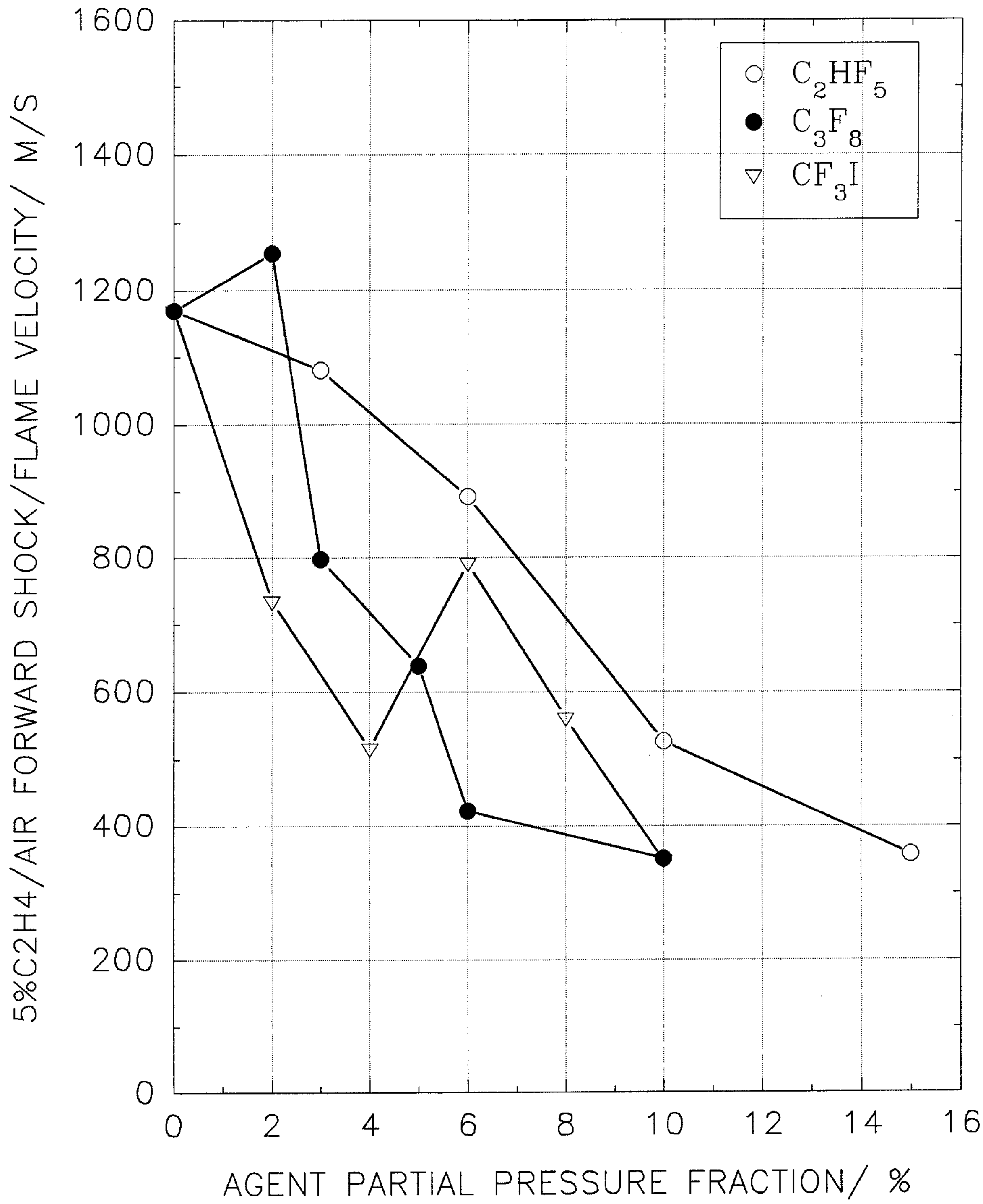


Figure 25 Relative shock/flame velocity suppression performance in the lean ethene/air mixture

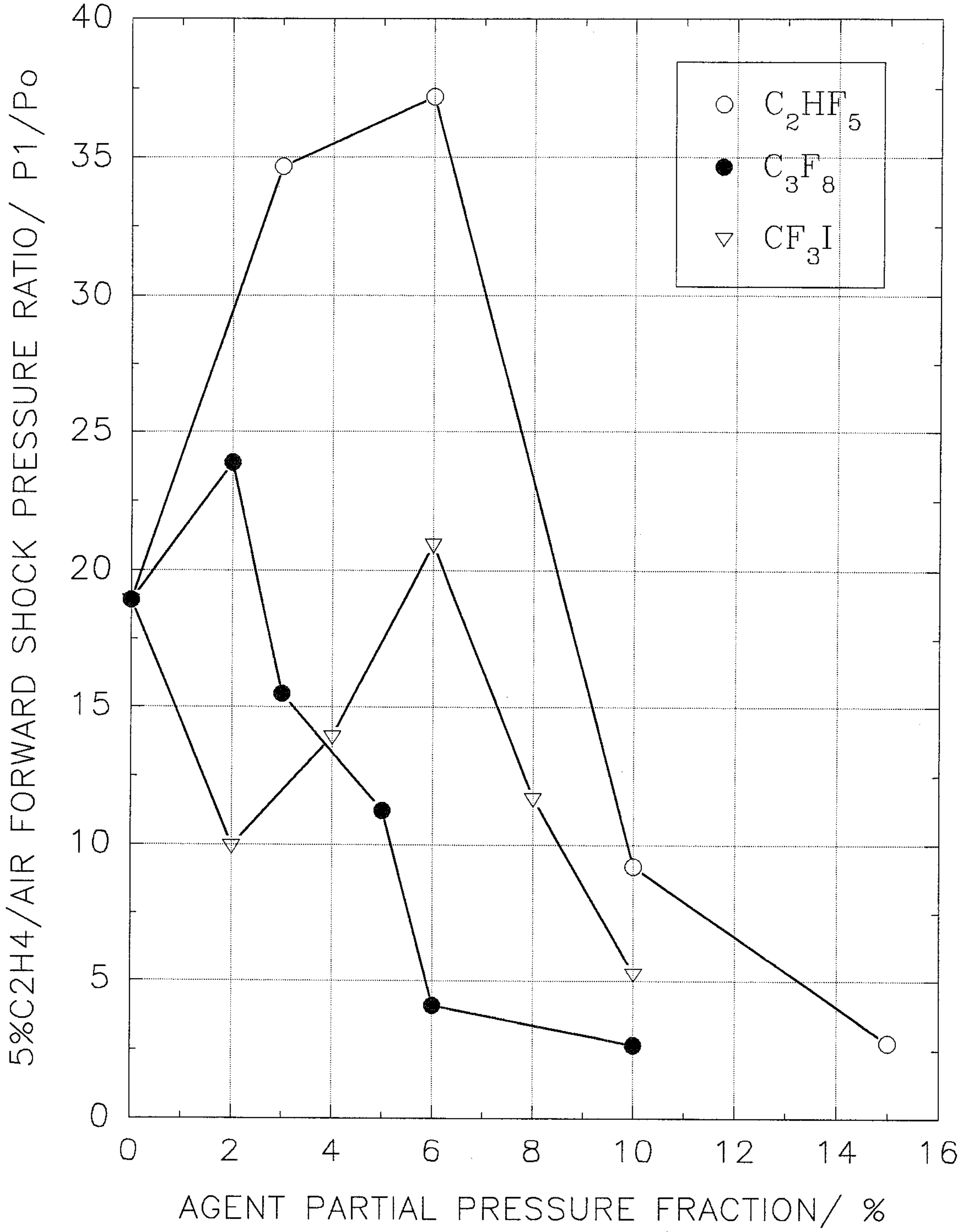


Figure 26 Relative shock pressure ratio suppression performance in the lean ethene/air mixture

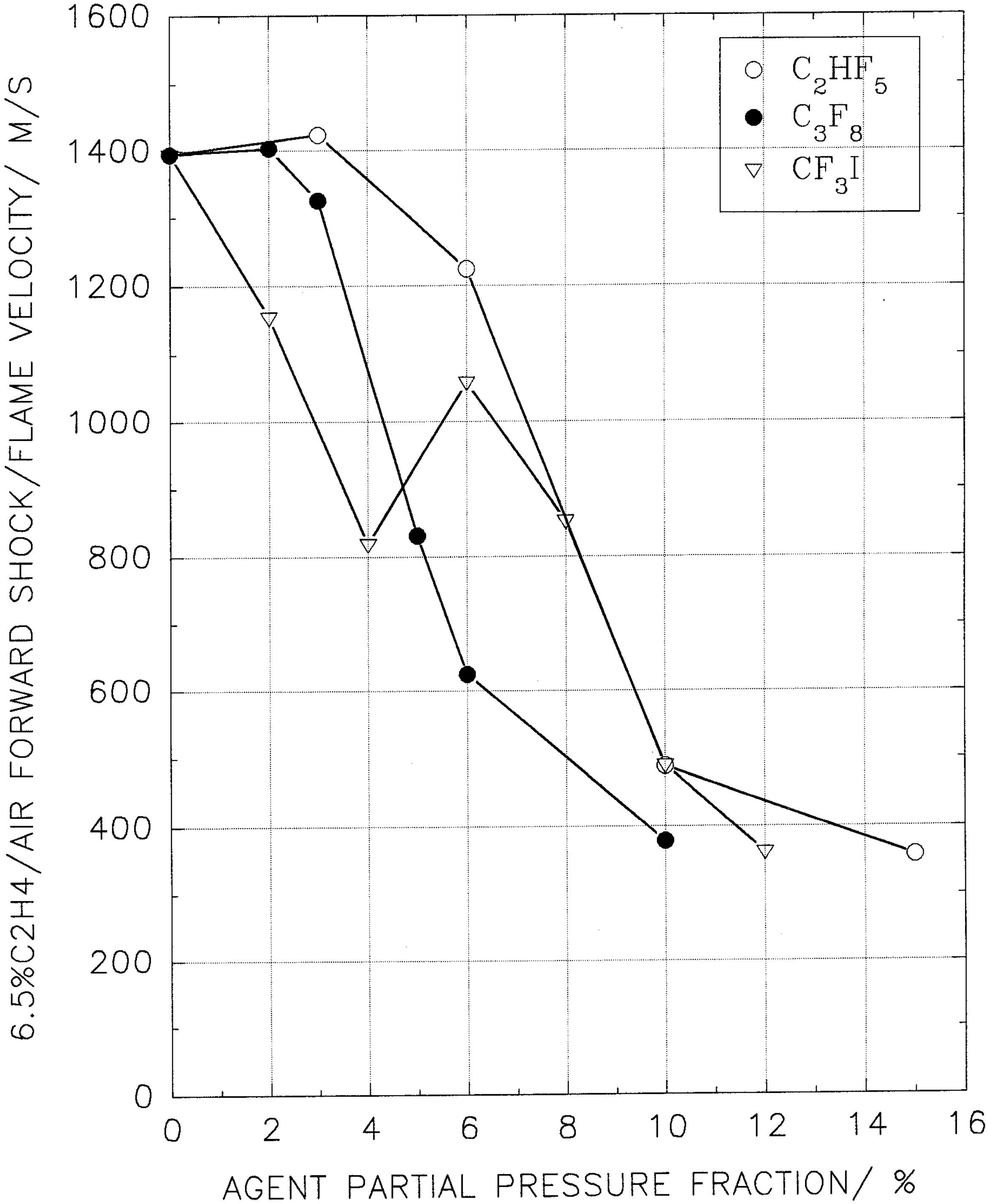


Figure 27 Relative shock/flame velocity suppression performance in the stoichiometric ethene/air mixture

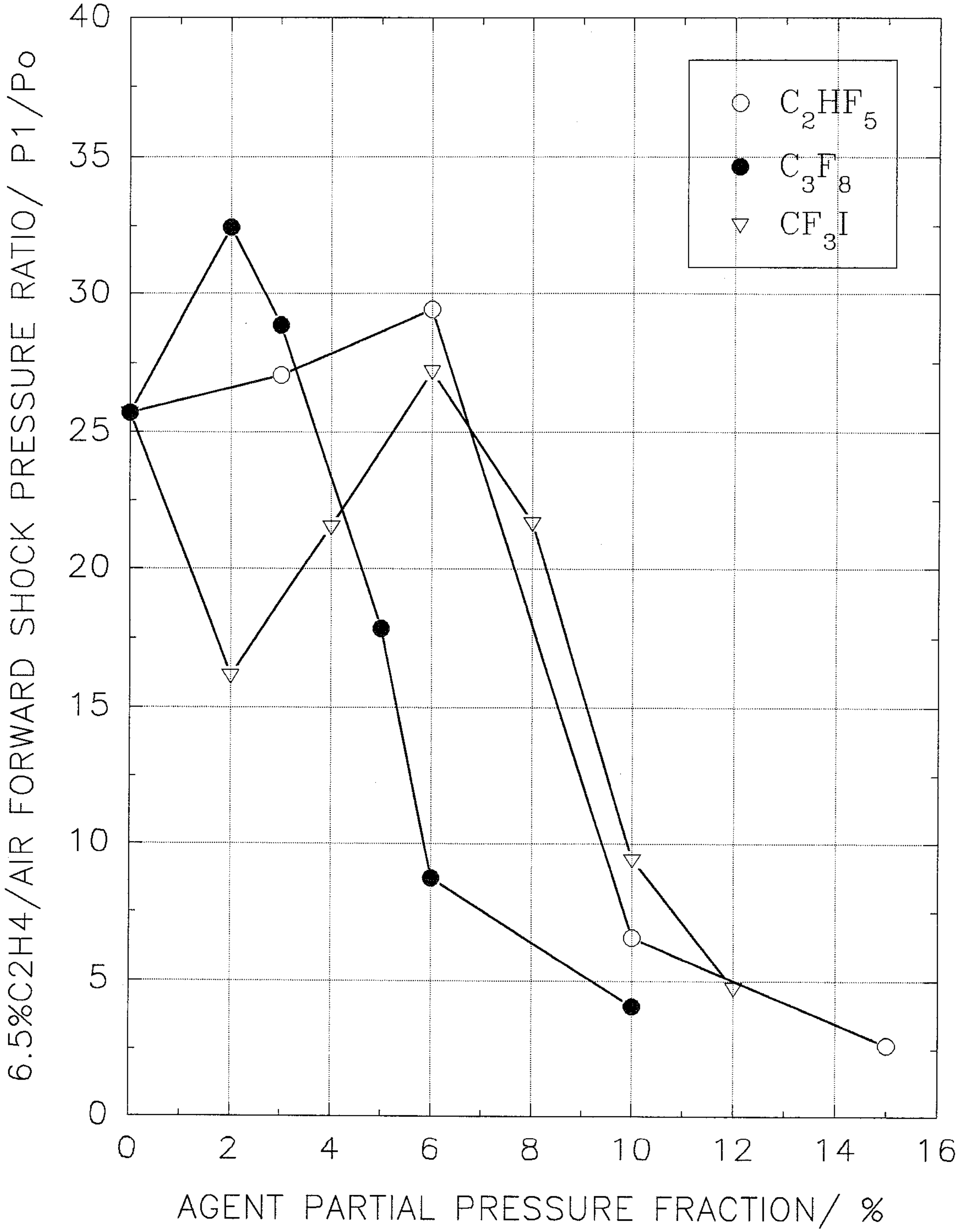


Figure 28 Relative shock pressure ratio suppression performance in the stoichiometric ethene/air mixture

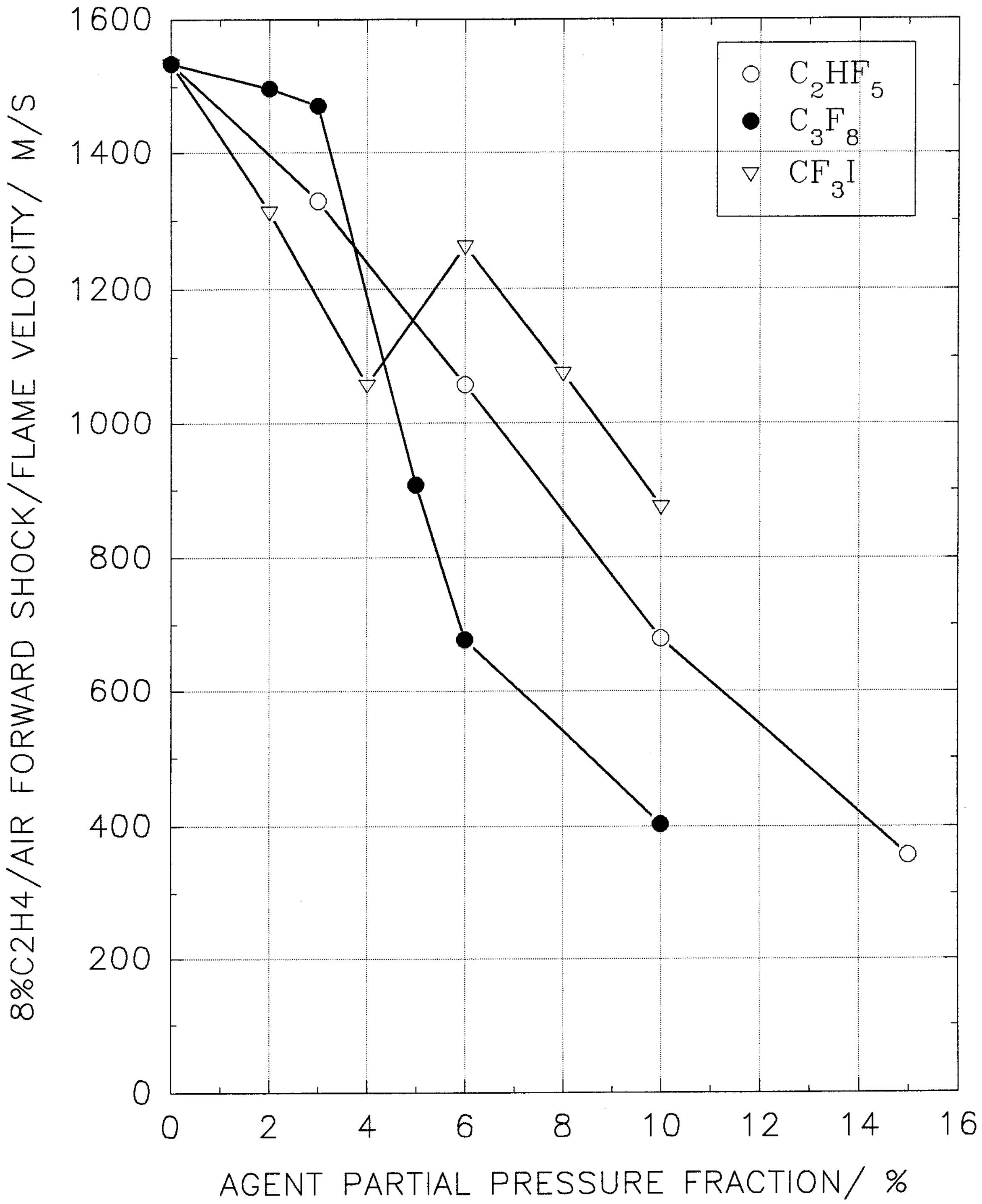


Figure 29 Relative shock/flame velocity suppression performance in the rich ethene/air mixture

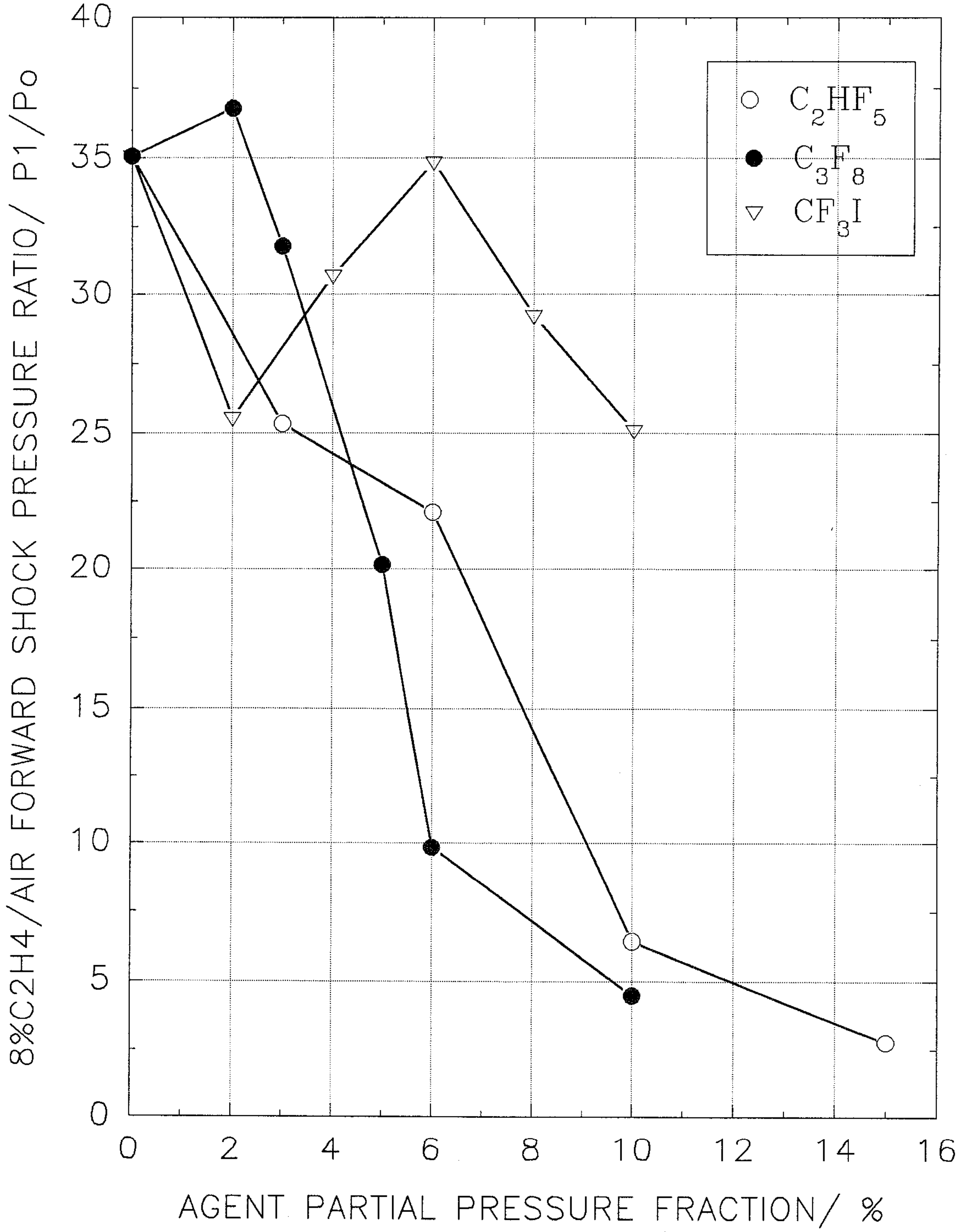


Figure 30 Relative shock pressure ratio suppression performance in the rich ethene/air mixture

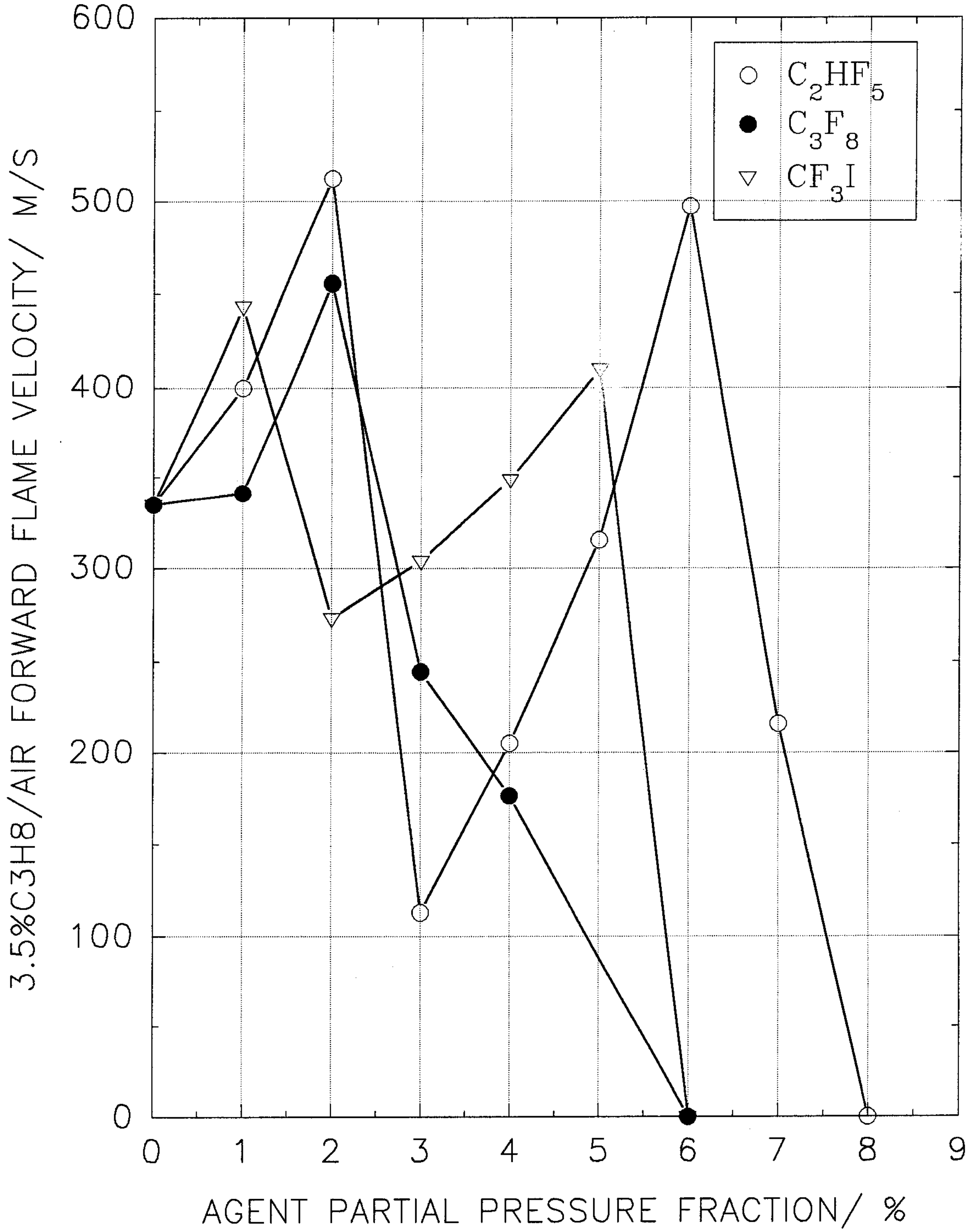


Figure 31 Relative flame velocity suppression performance in the lean propane/air mixture

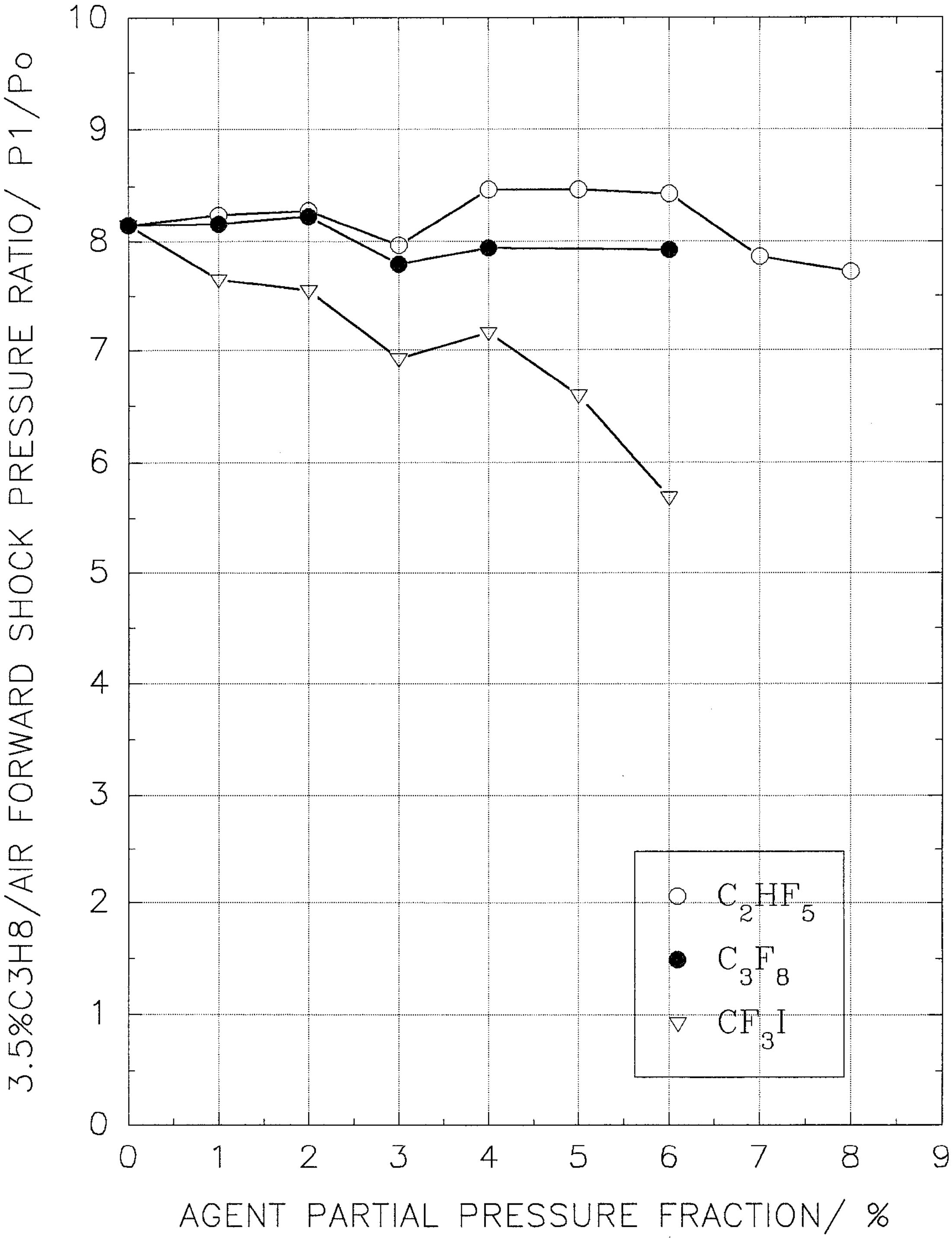


Figure 32 Relative shock pressure ratio suppression performance in the lean propane/air mixture

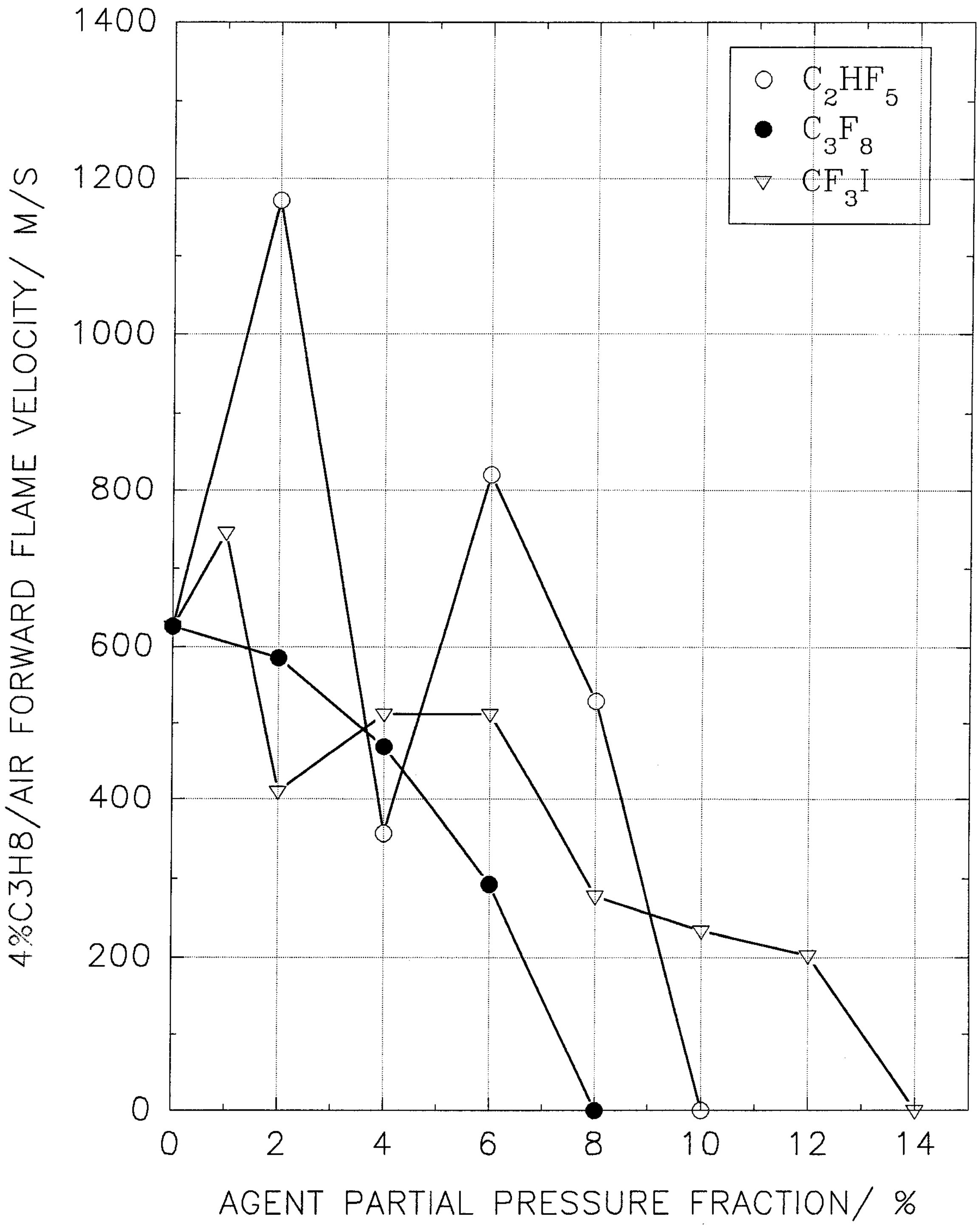


Figure 33 Relative flame velocity suppression performance in the stoichiometric propane/air mixture

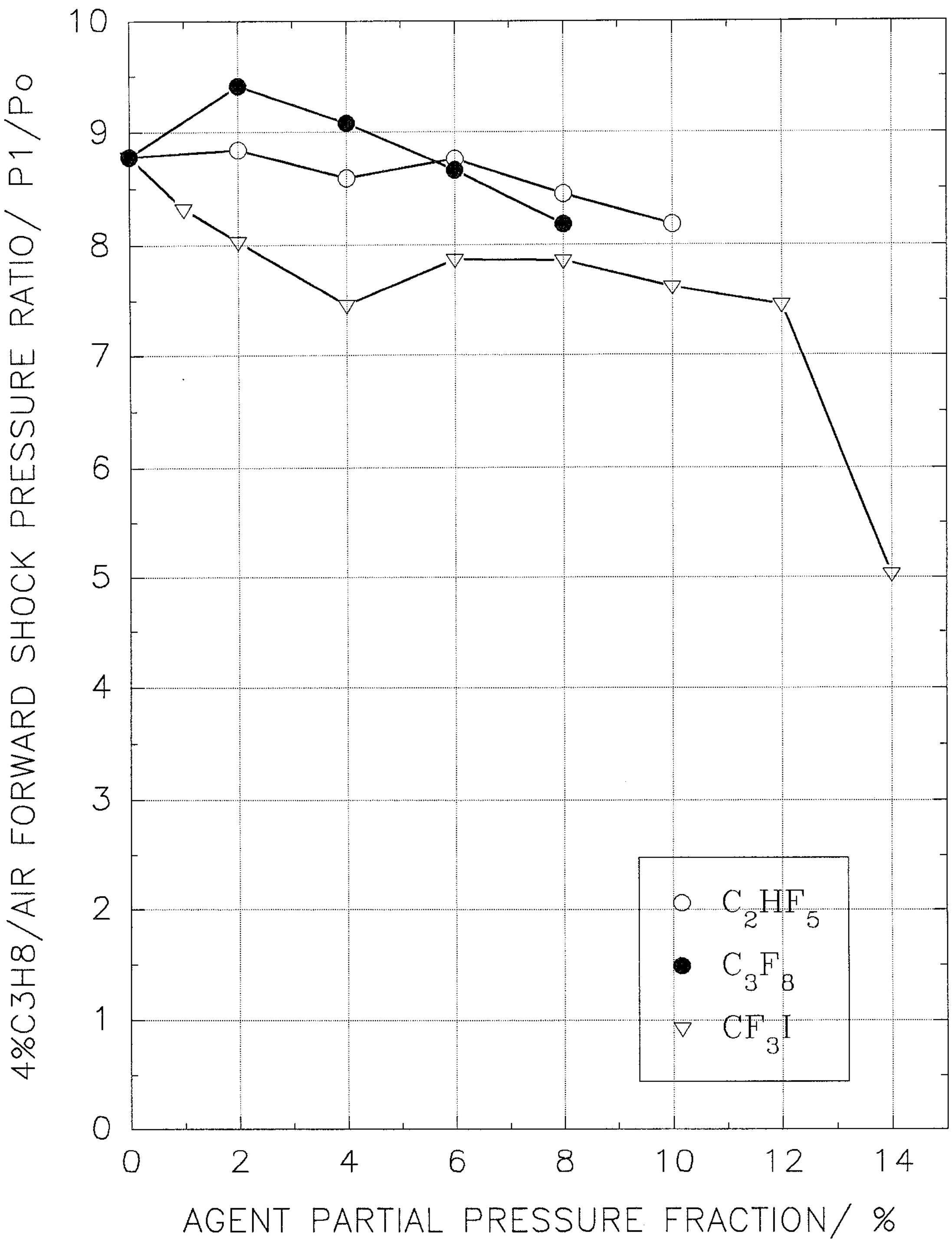


Figure 34 Relative shock pressure ratio suppression performance in the stoichiometric propane/air mixture

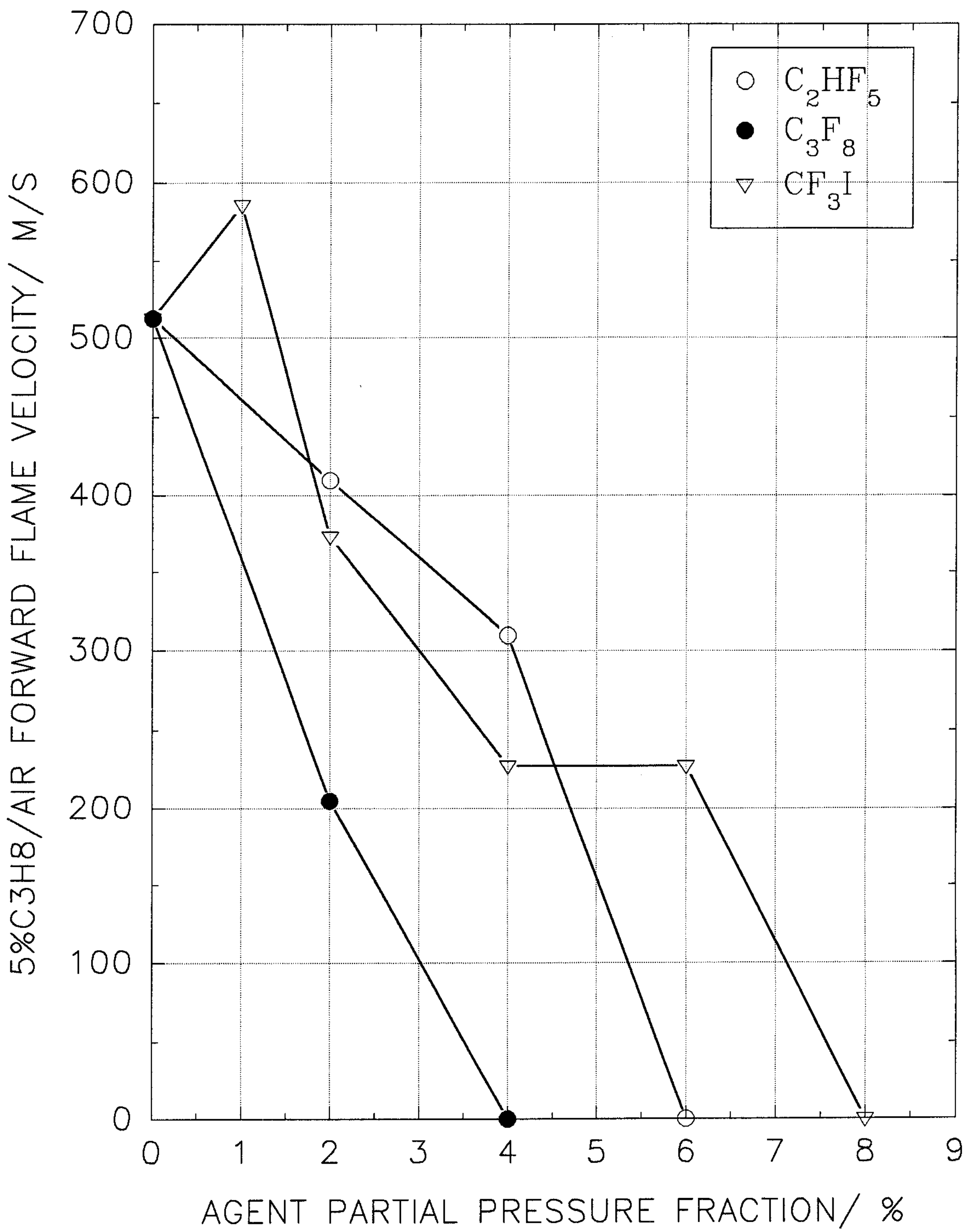


Figure 35 Relative flame velocity suppression performance in the rich propane/air mixture

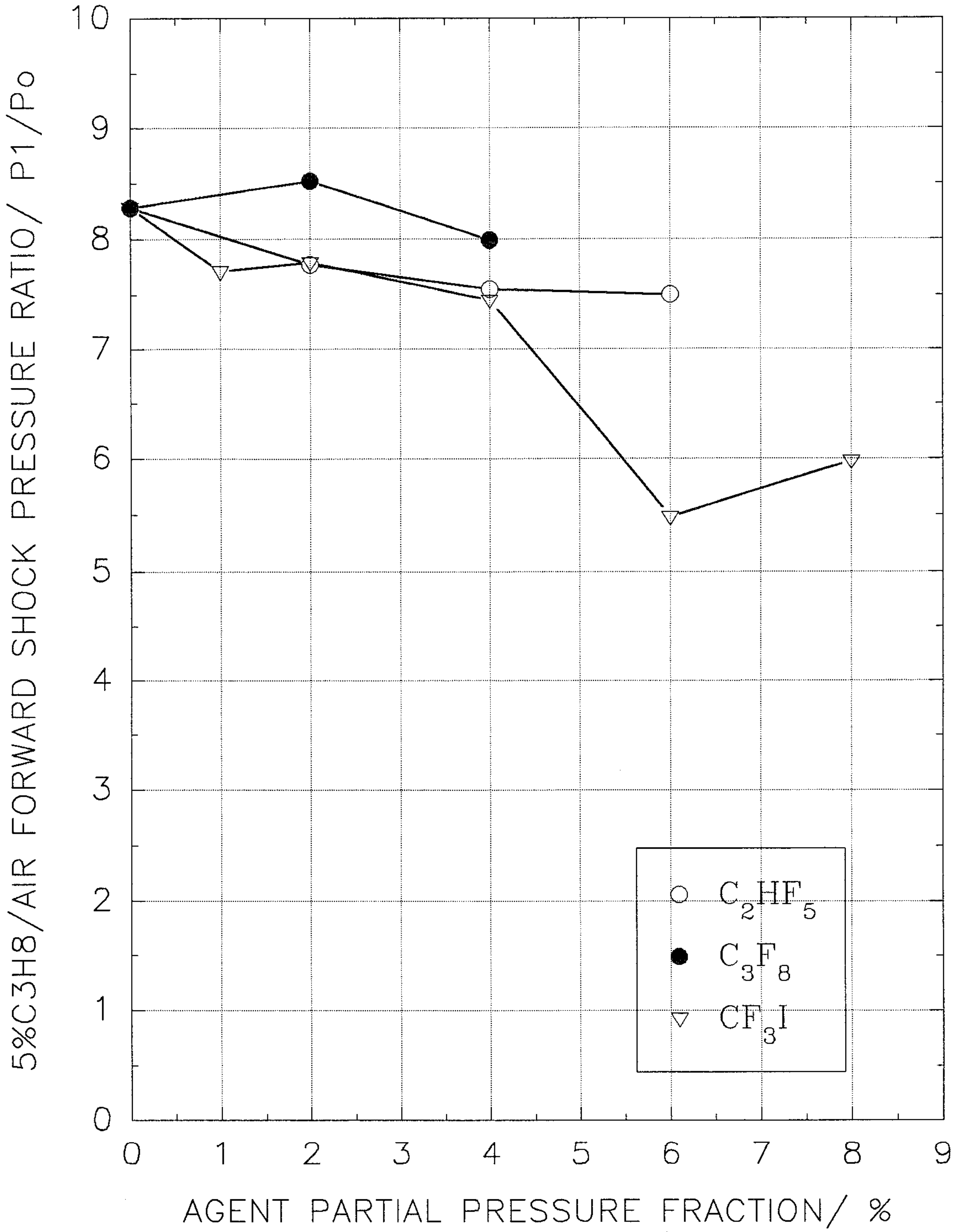


Figure 36 Relative shock pressure ratio suppression performance in the rich propane/air mixture

4.4.4 Relative Performance of C_2HF_5, C_3F_8, and CF_3I in the ethene/air mixtures. Relative performance of the three compounds has been assessed separately in the lean, stoichiometric, and rich ethene/air mixtures and is depicted in Figures 25 to 30. Figure 25 shows the comparison of the shock/flame velocities in the lean ethene/air mixture when the agents are added to the test section of the tube. One can see that only C_3F_8 causes some enhancement of the flame at low concentrations, while CF_3I causes enhancement at higher concentrations. The highest extinguishment concentration is required for C_2HF_5, and the extinguishment concentrations for C_3F_8 and CF_3I are the same.

Figure 26 displays the comparison of the shock pressure ratios in the lean ethene/air mixture in the presence of the three extinguishing agents. One can notice a dramatic difference in the pressure ratios for the three compounds. The most striking fact is a very high peak for C_2HF_5, which causes the pressure ratio to double. Such an increase does not occur for the other two compounds; however, to some extent they also promote the increase in pressure which becomes slightly higher than that for the pure combustible mixture. The typical values of the pressure ratios at extinguishment are between 3 and 5.

Figure 27 exhibits the velocities of the three compounds in the stoichiometric ethene/air mixture. A systematic decrease in the velocity occurs when the concentration of the agent is increased, with the exception of CF_3I, which causes a significant increase in that parameter at higher concentrations. The lowest extinguishing partial pressure fraction is required for C_3F_8, while C_2HF_5 required the highest.

Figure 28 demonstrates the respective shock pressure ratios in the mixture. Interestingly, the highest pressure ratio at small concentrations occurs for C_3F_8, which does not contain hydrogen. The addition of C_2HF_5, even up to 6%, also causes some increase in pressure ratio. Adding CF_3I initially causes significant drop in pressure ratio, but at higher concentrations the pressure ratio reaches the value characteristic for C_2HF_5. At the extinguishing concentrations the typical values of the pressure ratios are between 3 and 5.

Figure 29 shows the velocities of the shock/flame system in the rich ethene/air mixture. The addition of the agents causes a systematic drop in the velocity, with the exception of CF_3I. The lowest extinguishing concentration is required for C_3F_8, which confirms the same high performance of this agent noticed in the lean and stoichiometric mixtures.

Figure 30 displays the respective shock pressure ratios in the rich ethene/air mixture. Again, from the point of view of this parameter, C_3F_8 performs as the best extinguishing agent under highly dynamic conditions. However, at low partial pressure fractions C_2HF_5 appears to be better in the rich mixture and is comparable to CF_3I.

4.4.5 Relative Performance of C_2HF_5, C_3F_8, and CF_3I in the propane/air mixtures. Relative performance of the three compounds has been assessed separately in the lean, stoichiometric, and rich propane/air mixtures and is depicted in Figures 31 to 36. Figure 31 demonstrates the flame velocities in the lean propane/air mixture. The complex behavior of the flame is seen for all the compounds tested. Their presence cause the occurrence of extrema both at lower and higher concentrations. The velocities at the extrema are significantly higher than those for the pure combustible mixture. The highest extinguishing concentration is required for C_2HF_5. The other two compounds exhibit the same extinguishing value. On the average, the lowest velocity values are achieved with C_3F_8.

Figure 32 displays the shock pressure ratios in the lean propane/air mixture. Here, the most effective in attenuating the shock is CF_3I, which significantly decomposes on the passage of the shock. For this compound, the pressure ratio drops systematically down to the value 5.5. The other two compounds cause similar behavior of the pressure ratio which remains approximately constant when the agents are added. However, C_3F_8 appears to be a better performer.

Figure 33 shows the flame velocities in the stoichiometric propane/air mixture. The figure again proves the complex dependence of the flame velocity for the compounds with the exception of C_3F_8.

Both C_2HF_5 and CF_3I exhibit several extrema, which indicates that a complex chemical mechanism takes place in this case. The shape of the suppression curve for C_3F_8 is monotonic. The highest extinguishing concentration is required for CF_3I, the lowest one is required for C_3F_8.

Figure 34 depicts the shock pressure ratios in the stoichiometric propane/air mixture. One can see that CF_3I is the compound giving the lowest pressure ratio on the passage of the shock through the mixture. It drops dramatically near the extinguishing concentration to a value 5. The other two compounds do not cause such significant pressure ratio changes, and C_3F_8 even increases it slightly at low concentrations.

Figure 35 shows the flame velocities in the rich propane/air mixture. CF_3I gives the highest extinguishing value, 8% by volume, of all the agents studied. Also, under these conditions it causes enhancement at low concentration. The best suppressant proves to be C_3F_8, which exhibits an extinguishing value of 4%.

Figure 36 displays the shock pressure ratios in the rich propane/air mixture. Here also, CF_3I gives the greatest attenuation of the shock passing through the mixture. Especially at the extinguishing concentration CF_3I brings the pressure ratio down to 5.5, while the other two compounds do not affect that parameter significantly.

5. Summary and Conclusions

Alternatives to halon 1301 for protection of aircraft dry bays were ranked previously (Grosshandler et al., 1994) according to how well each could suppress a laboratory turbulent spray flame and a quasi-detonation. The experiments were designed to cover the range of conditions that might occur following the penetration by an incendiary device of a fuel cell adjacent to a dry bay. High over-pressures (37:1) were measured when HFC-125 was used to suppress a lean C_2H_4/air quasi-detonation. The range of initial conditions that lead to a worsening of the situation rather than a lessening of the threat has been investigated in the current study.

Pressure increases greater than a few atmospheres had not been observed in previous full-scale dry bay tests, and ratios of the order of 7:1 were the maximum pressure increases observed in fuel tank ullage suppression studies. The detonation/deflagration tube facility has been modified to operate over this less severe range of conditions. Pressure ratios below 9:1 were generated routinely for lean, stoichiometric and rich mixtures. These lower pressures were achieved by removing the spiral insert in the test section and by replacing the more reactive ethene with propane, which is also a better simulant of vaporized jet fuels. The flame speed was monitored close to the entrance of the test section to better assess the immediate impact of the suppressant on the flame. Previously, incident shock speeds over 1500 m/s were recorded. The current experiments with propane as fuel yielded uninhibited flame speeds between 300 and 600 m/s, much closer to the hundreds of meters per second estimated to occur in the full-scale dry bay experiments. A further modification to the facility has been the doubling of the test section length, to 5 m, which has increased the time required for the incident shock to reflect back into the turbulent flame front. This arrangement has allowed the incident shock speed and pressure ratio, the turbulent flame speed, and the conditions behind the reflected shock wave all to be monitored. The reflected shock wave was always found to be stronger than the incident wave, and, with no agent present in the test section, led to a detonation for a range of initial stoichiometries. Thus, with a single shot, we were able to observe the performance of the suppressant under moderate and highly dynamic conditions.

The table on the following page summarizes the results of all the detonation/deflagration experiments done with the three agents in this and the earlier NIST study. The suppression conditions are defined as the partial pressure of agent in the test section necessary to either totally quench the radiation from the reactants or to reduce the pressure ratio to the value had 100% nitrogen been used. The peak pressure ratios and reaction wave speeds refer to the maximum in the plots of pressure ratios (or velocities) versus agent partial pressure fractions. The agent percent is the partial pressure fraction where the maximum in reached. In most cases, small amounts of agent increased the pressure and reaction wave velocity. A value of 0% implies that the maximum is attained solely at the uninhibited condition. Generally speaking, the ethene quasi-detonation requires considerably more agent to extinguish than the turbulent propane flame; the stoichiometric mixtures require more agent than either rich or lean conditions; C_3F_8 (FC-218) requires the lowest partial pressure fraction to totally suppress both quasi-detonations and turbulent flames; C_2HF_5 (HFC-125) is the least effective suppressant of a quasi-detonation; and CF_3I is the least effective compound for total suppression of stoichiometric and rich turbulent propane flames. The highest pressure ratio observed (and the main reason for conducting the study) was for the lean ethene quasi-detonation with 6% C_2HF_5 added. HFC-125, when added to the stoichiometric turbulent propane flame at a partial pressure fraction of 2%, greatly accelerated the speed of the reaction wave, but did little to enhance the pressure build up.

Summary of Experimental Results in Detonation/Deflagration Tube

Parameter	Agent	Fuel and Equivalence Ratio					
		Ethene[a] $\Phi = 0.75$ Quasi-detonation	Ethene[a] $\Phi = 1$ Quasi-detonation	Ethene[a] $\Phi = 1.25$ Quasi-detonation	Propane[b] $\Phi = 0.86$ Turbulent Flame	Propane[b] $\Phi = 1.0$ Turbulent Flame	Propane[b] $\Phi = 1.25$ Turbulent Flame
Maximum Pressure Ratio[c] (@ partial pressure %)[d]	none	18 (0%)	26 (0%)	35 (0%)	8.1 (0%)	8.8 (0%)	8.3 (0%)
	N_2	2.5 (100%)	3.5 (100%)	[g]	4.5 (100%)	4.6 (100%)	4.5 (100%)
	C_2HF_5	37 (6%)	29 (6%)	35 (0%)	8.5 (4%)	8.8 (2%)	8.3 (0%)
	C_3F_8	24 (2%)	33 (2%)	37 (2%)	8.2 (2%)	9.5 (2%)	8.5 (2%)
	CF_3I	21 (6%)	27 (6%)	35 (6%)	8.1 (0%)	8.8 (0%)	8.3 (0%)
Maximum Reaction Wave Speed[e], m/s (@ partial pressure %)[d]	none	1170 (0%)	1400 (0%)	1530 (0%)	330 (0%)	620 (0%)	510 (0%)
	N_2	0 (100%)	0 (100%)	[g]	100 (100%)	100 (100%)	50 (100%)
	C_2HF_5	1170 (0%)	1410 (3%)	1530 (0%)	510 (2%)	1180 (2%)	510 (0%)
	C_3F_8	1250 (2%)	1400 (2%)	1530 (0%)	460 (2%)	620 (0%)	510 (0%)
	CF_3I	1170 (0%)	1400 (0%)	1530 (0%)	450 (1%)	740 (1%)	590 (1%)
Suppression Partial Pressure Percent[f]	N_2	40%	[g]	[g]	[g]	[g]	[g]
	C_2HF_5	13 to 15%	13 to 15%	13 to 15%	7.5 to 8%	9 to 10%	5 to 6%
	C_3F_8	8 to 10%	> 10%	> 10%	5 to 6%	7 to 8%	3 to 4%
	CF_3I	> 10%	> 12%	13 to 14%	5.5 to 6%	13 to 14%	7 to 8%

[a] 2.5 m test section, with spiral insert, measurement location 2.2 m into test section
[b] 5.0 m test section, without spiral insert, measurement location 0.3 m into test section
[c] ± 5% of value relative uncertainty
[d] ± 1% absolute uncertainty, and note that 0% implies no enhancement over zero inhibitor conditions
[e] ± 11% of value relative uncertainty
[f] ± 1% absolute uncertainty, based upon no flame radiation or pressure ratio equal to value attained by 100% N_2
[g] no data available

The following statements can be made based on the results obtained:

a. Combustion and suppression processes in the premixed hydrocarbon/air systems under highly dynamic conditions can be more effectively studied in the modified two-sectional tube, permitting clear discrimination of the combustion modes and performance among various gaseous extinguishing compounds.

b. There is a significant difference in combustion behavior between propane/air and ethene/air mixtures: the combustion modes at higher velocities overlap totally in the ethene/air mixture for the two geometric configurations while the propane/air mixture is characterized by a clear separation between the combustion modes for the two arrangements. Also, the regime of equivalence ratios for which combustion is detectable in the tube is much broader for the ethene/air mixture. Furthermore, a detonation was unable to develop in the propane/air mixture when the spiral insert was taken out of the tube.

c. The ethene/air flame in the quasi-detonation wave under suppression very closely follows the shock wave with the same velocity. The distance between the flame and the shock increases with the amount of an extinguishing agent. At extinguishment, the flame disappears, while the residual shock still exists.

d. The presence of a hydrogen-containing suppressant in the ethene/air mixture results in a significant increase in pressure ratio relative to that for the pure combustible mixture. The phenomenon occurs also for the compound not containing hydrogen atoms at relatively lower concentrations. The impact is generally weaker for stoichiometric and rich mixtures than it is for lean mixtures.

e. C_3F_8 is the most effective extinguishing compound in suppressing and attenuating flame/shock systems in the lean, stoichiometric, and rich ethene/air mixtures under highly dynamic conditions in the detonation/deflagration tube.

f. Depending on their concentrations, the presence of the three extinguishing compounds in the propane/air mixtures causes the flame to be either enhanced or suppressed, often with complex extrema exhibited. The behavior is however diminished when the mixture becomes richer in fuel content.

g. CF_3I is the best attenuating agent in decreasing shock pressure ratio in the lean, stoichiometric and rich propane/air mixtures. Such performance may be attributed to the significant endothermicity of the decomposition process of CF_3I during the passage of the shock through the mixtures under investigation.

The bottom line is, the conclusions drawn from the previous NIST study have been confirmed. FC-218 provides the most consistent performance over the widest range of fuel/air mixtures and tube geometries. The CF_3I has the greatest positive impact at low partial pressure fractions, but exhibits non-monotonic behavior of flame speed and shock pressure ratio at increasing concentrations. The dangerously high over-pressures previously exhibited by HFC-125 were not observed during suppression under more moderate (and realistic) combustion conditions. Considering these results alone, all three agents remain viable candidates for dry-bay applications.

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